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MOTHER LODE AND SIERRA NEVADA BATHOLITH

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ABSTRACT

A mineralized and silicified zone which dips more gently than the wall rock and is accompanied by reverse faulting or thrusting is defined as a "mother-lode structure." The western border of the Sierra Nevada batholith is accompanied by a belt of such structures. A tripartite arrangement which coincides with three distinctly different portions of the batholith can be recognized in this belt: (1) a southern portion of scattered lodes within the boundaries of the widest portion of the batholith; (2) a medial continuous zone (the Mother Lode proper) west of the batholith; and (3) a northern extension of scattered, rich lodes which are closely related to the contacts of scattered and small massifs. The divisions of the batholith are believed to be accidental and due to a northward plunge of the mass; lower levels are exposed in the southern region and higher levels in the north. Gold production and mining values increase from south to north and seem to be highest where the shallowest levels of the batholith are encountered. The plunge of the pluton would explain why the southern area is almost devoid of paying gold deposits.

The first appearance of a uniform Mother Lode trend is indicated by a series of intrusions which accompanied a post-Carboniferous and pre-Jurassic orogeny.

INTRODUCTION

The Sierra Nevada of California is accompanied along its western foothills by a zone in which gold-bearing quartz veins are abundant. This zone is continuous and sharply defined only between Mariposa and Placerville, and was called the "Mother Lode" because of its dominating rôle as a primary source of gold. The Mother Lode, the scattered gold quartz lodes north of it, and the gold prospects south of the lode all appear on or near the western boundary of the Sierra Nevada batholith. Consequently it has been held that the magma

was the ultimate source of the gold. This gives rise to several questions: (1) During which stage of the emplacements of the batholith have the lodes developed? (2) Do the several channels of ore-bearing solutions have any relation to the mechanism of intrusion? (3) Why is the Mother Lode zone restricted to the middle portion of the western border of the batholith? (4) Why are the genetically identical lodes farther north scattered and unconnected, and why are there no corresponding rich lodes along the southern part of the border?

To answer these questions requires a broad structural survey of the batholith and its surroundings. Such a survey was begun in 1930. One section from Mono Lake to Mariposa, California, was mapped in detail and will be referred to as the "Yosemite Section." A second section, approximately 110 miles to the north and parallel to the first one, was mapped in less detail, for comparison between Grass Valley and Donner Lake. Shorter, partial sections cross the eastern slope of the Sierras near Bishop and Sonora Pass. Several shorter profiles cross the Mother Lode near Mariposa, Bagby, Coulterville, Priest, Jacksonville, Sonora, Carson Hill, and other localities. At random observations were made over a large area between Grass Valley and Mariposa.

Approximately 16 months were spent in the field, and several years have been required to work up the results, owing to the complexity of the problems. Several short papers have been published,[1] preliminary to the main report on the Sierra Nevada batholith now in preparation. The present paper, which deals with the structures of the western foothills of the Sierra Nevada and the Mother Lode region, comprises only one phase of the whole investigation, namely, the relation between the batholithic intrusion and the origin and structure of the Mother Lode zone.

The funds for the beginning of the project were given by the

[1] Ernst Cloos, "Der Sierra Nevada Pluton," *Geologische Rundschau*, Vol. XXII (1931), No. 6, pp. 372–84; "Structural Survey of the Granodiorite South of Mariposa, California," *Amer. Jour. Sci.*, 5th ser., Vol. XXIII (1932), pp. 289–304; "Feather Joints as Indicators of the Direction of Movements on Faults, Thrusts, Joints and Magmatic Contacts," *Proc. Natl. Acad. Sci.*, Vol. XVIII (1932), No. 5, pp. 387–95; "Structure of the Sierra Nevada Batholith," *XVI Intl. Geol. Cong. Guidebook 16* (1933), pp. 40–45.

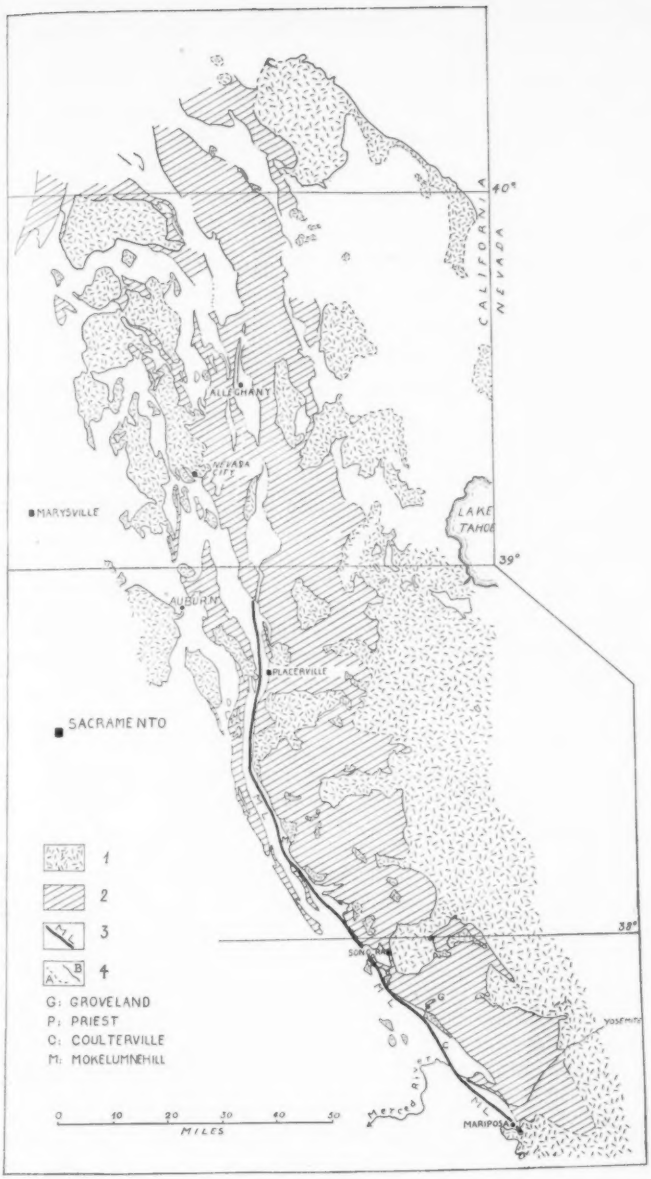

FIG. 1.—Relation of batholiths, Calaveras formation, and Mother Lode zone in the northern Sierra Nevada. Legend: *1*, batholithic rocks; *2*, Calaveras formation (Carboniferous); *3*, Mother Lode zone; *4A*, contacts covered by younger volcanics; *4B*, contacts exposed.

Notgemeinschaft der Deutschen Wissenschaften in Berlin. The project was continued with the help of the National Research Council. To these organizations the writer wishes to express his sincere thanks.

THE ROCKS OF THE REGION

The petrology of the Mother Lode district and the Sierra Nevada batholith has been given very clearly by Knopf, Lindgren, Turner, Ransome, and many others,[2] and only certain phases need be considered here. The major formations are the Calaveras (Carboniferous) and Mariposa (Jurassic) series with accompanying metavolcanics in large quantities. The Calaveras shows higher metamorphism than the Mariposa.[3] Probably folding took place after sedimentation of the Carboniferous and before the Jurassic was deposited. Aside from evidence given by Knopf and Ferguson, structures occur which support their views and may permit a relative age determination.

Mariposa and Calaveras conglomerates.—Both formations contain conglomeratic layers in abundance. The conglomerates within the Mariposa formation are unstretched and consist largely of well-rounded pebbles.[4] Figure 2 shows a normal contact between two layers within the Mariposa formation $\frac{1}{4}$ mile southeast of Jacksonville. A conglomeratic layer forms pockets within a finer-grained graywacke. The normal bedding is not obliterated but only tilted into a vertical position. The left side was once below the right side. Metamorphism is very slight, schistosity not being developed.

Aside from the components described by Knopf,[5] the writer has

[2] Adolph Knopf, "The Mother Lode System of California," *U.S. Geol. Surv. Prof. Paper 157* (1929), pp. 1–88; Waldemar Lindgren, "The Gold-Silver Veins of Ophir, California," *U.S. Geol. Surv. 14th Ann. Rept.*, Part II (1894), pp. 243–84; "Nevada City Special," *U.S. Geol. Surv. Folio 29* (1896); "The Gold-Quartz Veins of Nevada City and Grass Valley Districts, California," *U.S. Geol. Surv. 17th Ann. Rept.*, Part II (1896), pp. 1–262; C. L. Moody, "The Breccias of the Mariposa Formation in the Vicinity of Colfax, California," *Univ. Calif. Publ. in Geol.*, Vol. X (1916–18), pp. 383–421.

[3] Knopf, *op. cit.*, p. 11; H. G. Ferguson and R. W. Gannett, "Gold Quartz Veins of the Alleghany District, California," *U.S. Geol. Surv. Prof. Paper 172* (1932), pp. 1–139.

[4] Moody has described breccias of the Mariposa formation (*op. cit.*). The beds observed by the writer are conglomerates, however.

[5] *Op. cit.*, p. 15.

found pebbles of quartzite, biotite and sericite schist, and folded gneissic rocks. Granitic rocks are abundant, and the view of Knopf and Ferguson seems well supported that they represent a pre-Mariposa phase of igneous activity. Several pebbles of hornblende porphyrite may have been derived from basic dikes which accompanied that intrusive phase.

The Calaveras conglomerates are strongly deformed and the pebbles elongated into cigar-shaped components. The ratio between the longest and shortest axes approaches 1 to 20 or 30. V. M. Goldschmidt[6] describes very similar stretched conglomerates from the footwall of the great Norwegian overthrust.

The deformation of the Calaveras conglomerates is independent of the distance from the batholith contact. It is regional and uniformly widespread over

[6] "Konglomeraterne in den Høifjeldskvartsen," *Norges Geol. Unders. Nr. 77* (1916).

FIG. 2.—Boundary between conglomeratic layer and graywacke in Mariposa formation (¼ mile southwest of Jacksonville). The primary contact is not disturbed by later metamorphism and is not cut by cleavage. (Compare with Figs. 4 and 5.)

the entire district. Furthermore, stretched pebbles of Calaveras origin are found in inclusions within the granodiorite. They are transgressed by small dikes and broken during the intrusion. Stretched conglomerates of a very similar character occur in great quantities near the eastern contact of the Sierra Nevada batholith between Tioga Pass and Mono Lake. Whether or not they are of Calaveras origin could not be ascertained by the writer.

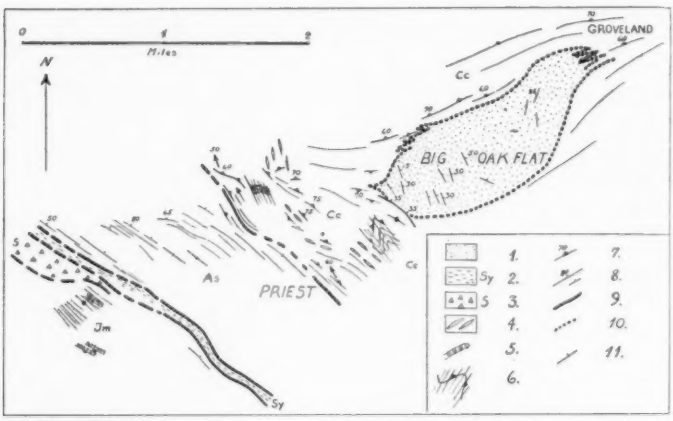

FIG. 3.—Structural map of the Mother Lode region near Priest. Legend: *1*, granodiorite of Big Oak Flat; *2*, syenite, following Mother Lode zone; *3*, serpentine; *4*, stretched pebbles in Calaveras conglomerate; *5*, unstretched pebbles in Mariposa conglomerate; *6*, folds in Calaveras schist with transgressing cleavage; *7*, strike and dip in Mariposa and Calaveras formations; *8*, strike and dip of schistosity in amphibolite schist; *9*, contacts; *10*, granodiorite contact; *11*, joints in granodiorite.

The contrast between the Mariposa and Calaveras conglomerates is most striking in the Priests Grade region west of Big Oak Flat because the formations occur in close proximity on either side of the Mother Lode zone (Fig. 3).

The process which resulted in this stretching was pre-Mariposa and pre-batholithic. A period of strong deformation has to be assumed between the Carboniferous and the Jurassic. This period is older than the Cordilleran revolution and may represent an orogeny equivalent to the late Carboniferous deformations elsewhere.[7]

[7] Ferguson and Gannett, *op. cit.*, p. 21.

According to Knopf, this phase was probably accompanied by igneous intrusions, of which the metadiorites may be the representatives. Since these intrusions show a close alinement parallel to the Mother Lode belt, it is possible that the first indications of such a distinct zone date as far back as late Carboniferous times and that later movements have repeatedly taken place along this important zone of fracturing and reverse faulting.

FIG. 4.—Pencil schist in Calaveras formation. Sullivan Creek southwest of Jamestown.

Slaty cleavage in the Calaveras formation.—The Calaveras sediments show a very conspicuous slaty cleavage which transgresses the bedding in many localities. It may best be seen at Sullivan Creek near Jamestown, where pencil schist has resulted from the intersection between bedding and slaty cleavage. Since the axes of folding dip steeply and the cleavage lies in the axial plane, the pencils also dip steeply (Fig. 4).

The strike of this cleavage seems fairly consistent over large areas, and mostly parallels the general northwest grain of the region. The dip, however, varies considerably within short distances. Although,

the cleavage cuts across the bedding, its dip changes with the dip of the beds. This is clearly seen in a road cut near Tuttletown, where the bedding is cut by cleavage at a high angle (Fig. 5). Veinlets of quartz follow the bedding. Folding is only slight and open. The cleavage forms two fans which converge toward the center of each fold in an anticline and syncline. The dip therefore changes rapidly between vertical and 50° toward either side. The cleavage was

FIG. 5.—Folded cleavage in Calaveras schist. Railroad crossing near Tuttletown. Scale: height of exposure, 6 feet.

formed before folding was completed in the final stage of deformation. The quartz veins were introduced later.

Assuming that the cleavage planes were formed as subparallel planes originally, it is possible to reconstruct the fold at the time of the developement of the cleavage. The folds were more open at that time than they are now. A very similar structure was described by Hans Cloos and Henno Martin[8] from the Rheinische Schiefergebirge in Germany. A close analysis and detailed survey of folding and cleavage permit a reconstruction of a large portion of the de-

[8] Hans Cloos and Henno Martin, "Der Gang einer Falte," *Fortschr. der Geol. u. Pal.*, Vol. XI (1932), pp. 74–88.

formative process with all its phases. A study of this kind may be very helpful in analyzing the structural history of the Calaveras formation.

MOTHER LODE STRUCTURE

The Mother Lode proper is usually considered to be a zone of intense reverse faulting. Gouge and breccia zones accompany the fault zone. The dip is eastward at varying angles, as a rule gentler than the wall-rock dip. The major fault zone is accompanied by more gently dipping veins which are arranged en echelon.

Reverse faults which are partly accompanied by veins and gold deposits occur outside the Mother Lode proper within its northern and southern extensions.[9] Their distribution is much more irregular, and a continuous zone cannot be traced.

A mineralized and silicified zone which dips more gently than the wall rock and is accompanied by reverse faulting or thrusting is referred to in this article as a "mother-lode structure."

Marginal thrusts.—Marginal thrusts are gently dipping reverse faults which are restricted to the margins of batholithic intrusions or block boundaries. They occur in great numbers and are arranged en echelon within the marginal zones. Individual displacements along the planes are small, but the total movement is considerable. The dip depends largely upon the dip of the major plane of movement, either the contact or fault zone.

The first description of marginal thrusts was given by Robert Balk in a study of granite intrusions in Vermont.[10] The border zones of those intrusions are filled with thrust planes along which the movements are directed outward from the intrusive center. Thrust planes of the same type were observed in large numbers and most perfect development in the Sierra Nevada batholith. They are most abundant along the eastern contact of the Yosemite section near Tioga Pass.[11] An interesting occurrence of thrusts in contact zones

[9] Ferguson and Gannett, *op. cit.*, pp. 70–72.

[10] Robert Balk, "A Contribution to the Structural Relations of Granitic Intrusions of Bethel, Barre, and Woodbury in Vermont," *15th Rept. of the State Geologist of Vermont* (1925–26), pp. 39–96.

[11] Hans Cloos, "Bau und Bewegung der Gebirge in Nordamerika, Skandinavien und Mitteleuropa," *Fortschr. der Geol. u. Pal.* Vol. VII (1928), pp. 257–59 and 260; Ernst Cloos, "Der Sierra Nevada Pluton," *loc. cit.*; "Feather Joints as Indicators of the Direction of Movements on Faults, Thrusts, Joints, and Magmatic Contacts," *loc. cit.*

has been observed by Mason L. Hill[12] in the San Gabriele Mountains.

The mechanical principle.—Marginal thrusts were probably formed as primary feather joints which later served as planes of movement and thus became thrust faults under lateral pressure.

An igneous contact may be compared with a normal or reverse fault. Magma masses are moved upward along the wall rock. Friction increases with progressing consolidation. Joints open at an early stage, their orientation depending upon the direction of the movements and the strike and dip of the contact planes. The area affected may increase with increasing consolidation of the magma. Joints may therefore overlap into the wall rock. If movements continue into the solid stage, the petrographic boundaries become mechanically unimportant, and a fracture zone, normal or reverse fault, may form within or outside the magma body. These zones are accompanied by joint systems which result from rotational deformation of a narrow belt in the immediate neighborhood of the fault.

Application to mother-lode structure.—The writer believes that there is a close resemblance between mother-lode structure and the arrangement of marginal thrusts or feather joints within contact or fault zones. Veins or mineral deposits may occur on the fault or in the accompanying fissures. Both possibilities are abundantly illustrated in the Mother Lode zone. Veins frequently follow reverse faults in the Mother Lode proper. Gently dipping feather joints seem to be more abundant in the northern and southern extensions.

A close relation between strike and dip of the batholith contact and the formation of mother-lode structures exists aside from the relation between master fault and feather joint. Gently dipping marginal thrusts cannot be expected in regions where the stress can be relieved by lateral spreading of the magma. In the southern part of the region the batholith contacts are largely flat-lying, and there the magma has spread laterally in many places.[13] Mother-lode

[12] Mason L. Hill, "Structure of the San Gabriele Mountains North of Los Angeles, California," *Univ. Calif. Publ. in Geol.*, Vol. XIX (1929–31), pp. 139–70.

[13] Ernst Cloos, "Structural Survey of the Granodiorite South of Mariposa, California," *loc. cit.*

structures are here confined to steeply dipping contacts between the granodiorite and wall-rock inclusions.

North of Mariposa, east of the Mother Lode proper, the contacts steepen and the batholith lies east of the system. The lateral component of movement is probably small and the movements are confined to a zone outside of the batholith. This zone roughly follows the boundary between the Carboniferous and Jurassic. Strongly metamorphosed sediments and metavolcanics are separated by the Mother Lode fault from younger and less metamorphosed sediments. The fault zone does not follow this boundary sharply but in places enters the blocks to the east and west. The direction of movement is toward the west, owing to the lateral pressure exerted by the batholith to the east.

The northern region is dominated by two batholiths, one at either side of the structure zone. Stresses were not so uniform as in the Mother Lode proper. Structures are largely dominated by smaller intrusives and the attitude of their contacts. Movements are directed toward the east and west.

JOINTING

The variety of joints in the Sierra Nevada is bewildering. A close inspection, however, shows more regularity and order in the numerous systems than would be expected at first sight. A simple registration of all joints, without a record of the associated rock structures like flow lines or planes, linear stretching, foliation, axes of folding, strike and dip of bedding, and cleavage, etc., is useless; but if the region is mapped with all its structural features, it can soon be seen that certain structures are associated with equivalent joints, and the recognition of dynamic boundaries permits classification of joint systems in time and space.

Most of the joints are locally restricted. In the category of local joints are the magmatic joints which can be related to the breaking phase of the rise of the magma,[14] together with the joints accompanying the normal and reverse faults. Folding and stretching was also

[14] Balk, "Structural Behavior of Igneous Rocks" (in preparation); Hans Cloos, "Einführung in die tektonische Behandlung magmatischer Erscheinungen (Granittektonik)," Part I (Berlin. Bornträger, 1925).

followed by jointing in definite directions. After elimination of such local joints a certain number of sets with a much wider distribution may remain unaccounted for. They constitute the regional joints. These are younger and superimposed on local joints. The gradual growth of dynamic units during consolidation permits the formation of larger structural features. The jointing problem in the Sierra Nevada will be treated in a separate paper.

Two distinct joint directions are obvious in addition to the Mother Lode system. A local one strikes northwest-southeast and dips

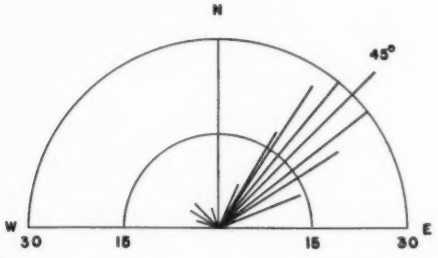

FIG. 6.—Strike diagram of basic dikes. Length of line indicates number of dikes measured in each 5° arc.

gently either toward the northeast or southwest. A regional system strikes northeast-southwest and northwest-southeast and dips steeply throughout the region. "Crossings" at Grass Valley[15] follow these directions, and basic dikes parallel these joints in large numbers. Figure 6 shows these dikes statistically. The northeast direction dominates the northwest trend. A set which follows the northeast-southwest direction was observed throughout the northern Sierra Nevada from Bishop to Lake Tahoe and from Fresno to Alleghany. It is the most persistent and regional arrangement of joints and also the youngest. Basic dikes indicate a relatively close association of this joint system with the latest phase of magmatic intrusion. Local deviations from the normal direction are due to local conditions. As a rule, however, these joints do not respect igneous or sedimentary boundaries.

[15] W. D. Johnston, Jr., and Ernst Cloos, "Structural History of the Fracture Systems at Grass Valley, California," *Econ. Geol.*, Vol. XXIX (1934), pp. 39–54.

The regional joints everywhere transgress the Mother Lode zone, and, since they are filled with basic dikes, prove that the lode as such is older than the joints and dikes. This means that it was formed before complete consolidation of the region and before the rest of the magmas were intruded.

GEOLOGIC SITUATION OF THE MOTHER LODE ZONE

The Mother Lode belt of California is usually understood to be a system of structures 1 mile wide and 120 miles long, reaching from Mariposa in the southeast approximately to Placerville in the northwest (Fig. 1). This may here be called the Mother Lode proper.[16] Mother-lode structures are not restricted to this zone, however, but occur farther to the north and south in the western foothills of the Sierra Nevada. Because of their similarity, these local structures of a much smaller order of magnitude are included in this study. It may, therefore, be more accurate to speak of a "zone of mother-lode structures" or a "larger Mother Lode zone," which comprises all the widely scattered occurrences of mother-lode structures—for instance, the gold quartz veins of Grass Valley and Nevada City or the Alleghany district. The trend of this larger Mother Lode zone follows the structural trend of the region, indicating a close relation to the configuration and emplacement of the Sierra Nevada batholith.

Three divisions of this larger Mother Lode zone, based on the structural significance of the units and their relation to the batholiths, are suggested.

DIVISIONS OF THE LARGER MOTHER LODE ZONE

1. *Mother-lode structures south of Mariposa.*—The Mother Lode proper is terminated south of Mariposa by an offshoot from the Sierra Nevada batholith.[17] This is the only location where the batho-

[16] F. L. Ransome, "Mother Lode District, California," *U.S. Geol. Surv. Folio 62* (1900); Knopf, *op. cit.*, pp. 1–88; O. P. Jenkins, "Report Accompanying Geologic Map of Northern Sierra Nevada," *Mining in California*, Vol. XXVIII, Nos. 3 and 4 (July–October, 1932).

[17] H. W. Fairbanks, "Geology of the Mother Lode region," *Calif. State Min. Bur. 10th Ann. Rept.* (1890), p. 30; Ernst Cloos, "Structural Survey of the Granodiorite South of Mariposa, California," *loc. cit.*

lith contact transgresses the Mother Lode zone. The batholith widens considerably from here southward, and the mother-lode structures occur within its main contacts. Even smaller lateral intrusives farther to the north do not transgress the zone. They may reach it, however; and their contacts may parallel its trend.

Occurrences of mother-lode structures within the boundaries of the batholith south of Mariposa are scattered, small, and local. They are abundant near the contacts between batholithic rocks and large inclusions of wall rock, but of little economic importance, although a large number of small mines and mining claims are listed in the report of the state mineralogist.[18]

2. *The Mother Lode proper between Mariposa and Placerville.* The Mother Lode proper is a continuous zone of narrow restriction and great distinctiveness which seems to indicate an important structural and formational boundary. Reverse fault movements can be traced along the entire zone. No rocks of Mariposa age (late Jurassic) were found east of the lode. The occurrences of the Calaveras formation (Carboniferous) west of the zone are restricted to a few narrow bands; the bulk of this complex lies to the east. It seems therefore obvious that the Mother Lode proper forms the boundary between these two formations in a general way.

Mother-lode structures are most pronounced in this zone and restricted to this narrow and continuous belt. Its extention and sharpness suggest a different origin from the southern or northern portions of the larger Mother Lode zone.

3. *Mother-lode structures north of Placerville.*—The Mother Lode proper ends north of Placerville, and a large number of scattered structures take its place. Individual structures are of the lode type but do not connect into a continuous zone, and occur within a much wider belt. This northern portion of the large Mother Lode zone resembles the southern portion, where the structures are also scattered and unconnected. A close relation to igneous contacts is evident, although the northern district lies outside of the batholiths or within their marginal zones.

[18] Mines and mineral resources of the counties of Fresno, Kern, Kings, Madera, Mariposa, Merced, San Joaquin, Stanislaus in *Calif. State Min. Bur. Bull. 71* (1915).

DIVISIONS OF THE BATHOLITH

The three divisions of the larger Mother Lode zone outlined above are paralleled by three individually different divisions of the Sierra Nevada batholith. It seems evident that each group of mother-lode

TABLE I

SUMMARY OF RELATIONS BETWEEN THE LARGER MOTHER LODE ZONE AND THE SIERRA NEVADA BATHOLITH

	Larger Mother Lode Zone (Structure and Mineralization)	Batholith
North of Placerville	Scattered zone of small structures between small massifs and within their marginal zones	Many small stock-like intrusions in a western and eastern group
	Rich mineralization	Contacts, steeply or outward-dipping High level exposed
	No uniform, but many local, structures	No uniform lateral pressure
	Movements eastward and westward	Eastern and western batholith
Between Placerville and Mariposa	Mother Lode proper. Continuous zone largely following reverse fault zone and formational boundary	Narrow pluton with protrusions toward the west. Dome structure, joint fans, marginal thrusts
	Increase of mineralization northward	Contacts steeply eastward dipping or vertical
	Uniform reverse fault with movements toward the west	Lateral pressure probably at maximum, probably because of narrow confinement and repeated intrusion into one chamber
South of Mariposa	Scattered small structures in the margins of large wall-rock inclusions. Mother-lode structures within batholith	Wide laterally spreading batholith. Transgressing Mother Lode proper
	Poor or no mineralization. Movements depend on local conditions	Contacts gently eastward dipping Low level exposed

structures was formed in close structural association with its neighboring portion of the batholith (Table I). The zones or divisions with which the structures may be associated grade into each other from south to north. Distinct boundaries cannot be drawn.

1. *The batholith south of Mariposa.*—The Sierra Nevada batholith widens considerably and abruptly south of the Merced River and Yosemite National Park. It transgresses the Mother Lode proper south of Mariposa and holds its width from here on southward (Fig. 1). The contacts dip gently toward the east and under the granodiorite. The batholith seems to have spread laterally over metamorphic sediments. The axes of folding dip north and northeastward under the batholith. Since folding is close, steep contacts alternate with flat ones. Dips as low as 20° prevail in synclines and anticlines; steep ones are seen on the flanks (Fig. 7).

The writer has not followed the western contact southward as far as would be desirable. It will be of great interest to follow these conditions into Fresno County and farther south. Studies of the literature on the region show that gently eastward-dipping contacts are quite usual in the southern portion of the batholith.[19]

The belt of metamorphic sediments which underlies large areas in the northern Sierra Nevada narrows southward and disappears in the southern half of the range. It is conceivable that these metamorphic series are missing here, or possibly are partly overridden by the batholith, as suggested by the widening of the batholith and its gently dipping contacts.

2. *The batholith east of the Mother Lode proper (between Mariposa and Placerville).*—The batholith is much narrower north of the Merced River. Large protrusions toward the west almost reach the Mother Lode near Sonora and farther north. In no place do they transgress it, however, the main batholith remaining east of the lode. The Yosemite section[20] has clearly shown that the composite pluton has grown in distinct periods, gradually widening its berth. Internal structures reveal a threefold longitudinal division into two domed regions and one asymmetrical western zone which dips eastward, paralleling the western contact. The dip angle is steep and not comparable with the more gentle dip angle in the southern district. Wall-rock inclusions within this region are scattered and form dividing septae between structural and petrographic units.

[19] *Calif. State Min. Bur. 10th Ann. Rept.* (1890).

[20] Ernst Cloos, "Der Sierra Nevada Pluton," *loc. cit.*, and "Structure of the Sierra Nevada Batholith," *loc. cit.*, sections.

3. *The batholith north of Placerville.*—North of the Placerville–Lake Tahoe highway the Sierra Nevada pluton resolves itself into a number of small stock-shaped intrusions. Wall-rock septa of considerable width separate the units. The apparent uniformity of the

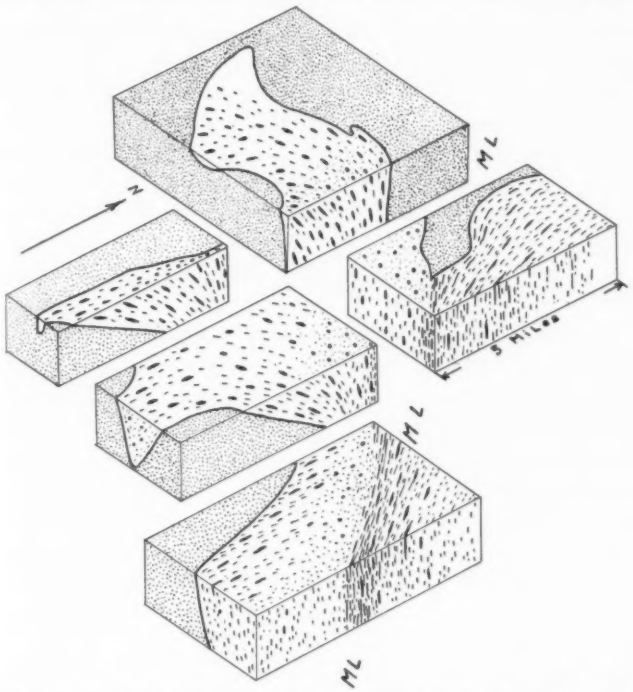

FIG. 7. Block diagram (schematic) of the transgression of the batholith south of Mariposa. The granodiorite follows synclines and avoids anticlines. The Mother Lode zone is traceable into the granodiorite in its flow structures. Legend: wall rock, stippled; granodiorite, light with flow structure; autoliths and xenoliths shown by dark spots; flow structure shown by dashes and dots.

batholith is lost. As in the Yosemite section, the units are of different age, the earliest intrusions being the western ones. Dome structure of flowage elements and joint fans were not observed.

A second group of stocks gains importance west of a wide sedimentary belt (Fig. 1). This group resembles the eastern one in

many respects. The same rock types are encountered, structures are similar, and both groups show evidence of entity.

The separating belt of sediments and volcanics is wide and seems to be more than merely a superficial partition within one batholith. It contains a large number of structures of the mother-lode type. Igneous contacts within both groups dip steeply or flare outward as at Grass Valley.[21]

The writer believes that the Sierra Nevada batholith plunges northward,[22] exposing lower levels in the Yosemite section and southward than in the Grass Valley–Lake Tahoe section. Inward-dipping contacts and dome structure at the center of the southern portion strongly suggest that the pluton boundaries as a whole converge downward. Vertical and outward-dipping contacts and the lack of dome structure in the northern portion indicate widening downward.

MINERALIZATION IN THE LARGER MOTHER LODE ZONE

The northward plunge of the batholith is accompanied by an increase of mineralization, as indicated in the recovered gold values in the larger Mother Lode zone (Table II). The southern portion seems almost devoid of paying gold deposits, partly because it lies within the boundaries of the batholith and partly because lower levels of the batholith are encountered. The Mother Lode proper shows the same increase as the entire region. The richest and deepest mines are found in the northern part. The region north of Placerville seems most favorably located, both structurally and with respect to the batholith level.

The values in Table II were taken from the state mineralogist's report. A computation of recoveries per square mile is arbitrary, but represents the situation more accurately than a simple statement according to accidental county boundaries.

AGE OF MOTHER-LODE STRUCTURE

Structural age determinations are difficult in the Mother Lode region because the zone itself has repeatedly served to accommodate

[21] Johnston and Ernst Cloos, *op. cit.*

[22] Ernst Cloos, "Sierra Nevada Batholiths and the Mother Lode Zone" (abst.), *Geol. Soc. Amer. Bull. 44* (1932), pp. 79–80.

stresses. Reopenings of the walls and several mineral generations have been observed by various geologists. A distinction, however, must be made between ore deposition and the structure itself. Gold deposits may be connected with the latest batholithic exhalations; the structure is older.

It is rather fortunate that the Mother Lode proper and the Sierra Nevada batholith meet at one point south of Mariposa. Here

TABLE II

MINERALIZATION IN THE LARGER MOTHER LODE ZONE*
(Gold production)

	Year		
	1894–95	1928–29	1930–33
Northern portion (north of Placerville) Area: 3,931 sq. miles	$ 8,578,969.00 or: $2,182.00 per sq. mile	$ 8,810,932.00 or: $2,215.00 per sq. mile	$14,097,670.00 or: $3,586.00 per sq. mile
Central portion (between Placerville and Mariposa) Area: 7,024 sq. miles	$10,212,565.00 or: $1,468.00 per sq. mile	$ 4,604,079.00 or: $655.00 per sq. mile	$ 7,154,214.00 or: $1,018.00 per sq. mile
Southern portion (south of Mariposa to Fresno) Area: 8,062 sq. miles	$ 385,568.00 or: $47.00 per sq. mile	$ 34,184.00 or: $4.00 per sq. mile	$ 37,570.00 or: $4.00 per sq. mile

* The northern portion includes: Nevada, Placer, Sierra, and Yuba counties; the central portion: Amador, Calaveras, Eldorado, Tuolumne, and Mariposa counties; the southern portion: Madera and Fresno counties.

a fault zone was not found within the granodiorite. Breccia, gouge and displacements of the usual order of magnitude are absent. The major movements must therefore have taken place before consolidation, perhaps during or before emplacement of the batholith. Primary shear zones and flexures, formed during an early phase of its consolidation, occur in the continuation of the Mother Lode proper within the granodiorite and can be traced for many miles (Figs. 7 and 9). This means that certain movements must have taken place before the magma was completely frozen.

Primary flexures located in the extension of the Mother Lode proper into the granodiorite are shown in Figure 9*a*. Primary foliation, accompanied by autoliths and xenoliths, is bent into a second-

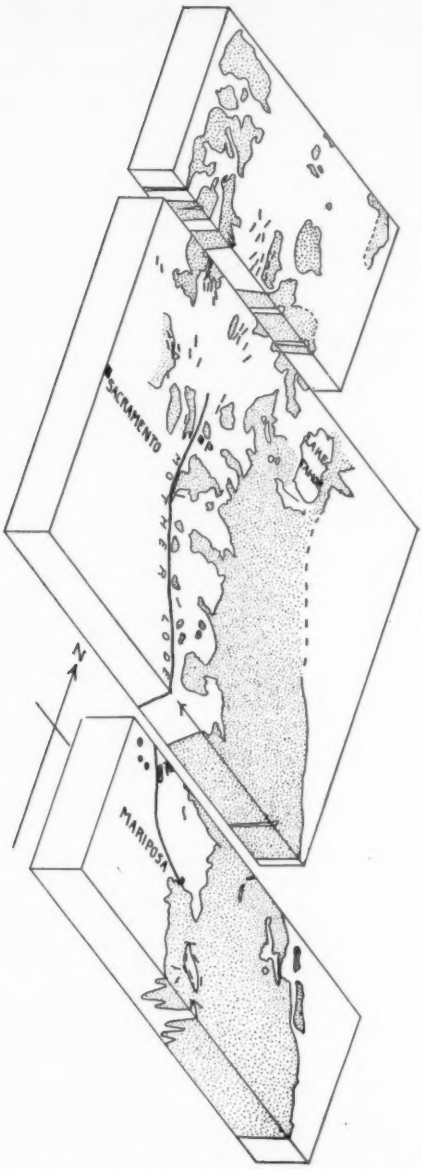

FIG. 8.—Block diagram of the northern portion of the Sierra Nevada batholith. Short heavy lines: scattered mother-lode structures. Stippled area: batholith rocks.

ary direction of movement. The boundaries of the flexure zone are indistinct and gradational. Such zones could be possible only if the magma were in a plastic and flexible condition during their forma-

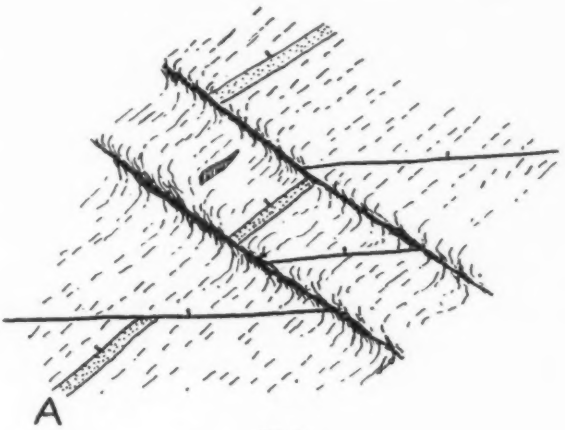

FIG. 9a

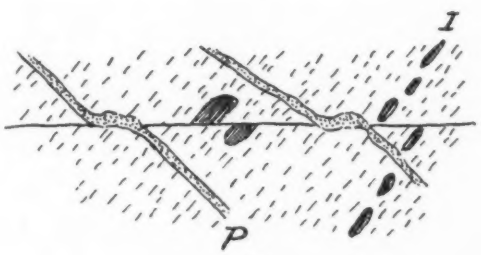

FIG. 9b

FIGS. 9a AND b.—Flexures and faults within the granodiorite. Early, plastic phase. Legend: *A*, aplite; *P*, pegmatite; *I*, inclusions.

tion. Pegmatite dikes which follow a flexure zone for a short distance may be seen in Figure 9*b*.

Had the batholith and its wall rocks been consolidated before the Mother Lode movements took place, the lode would not necessarily be terminated south of Mariposa. The structure ought to be found

in continuity, even if veins and fissures were barren, because of their situation within the igneous mass. Such barren quartz veins occur along the western contact of the Big Oak Flat intrusive (Figs. 3 and 10). They follow typical Mother Lode joints, and thrust movements can be observed in places. Mining in this region has proved that gold in small quantities occurs if the veins enter the surrounding wall rocks.

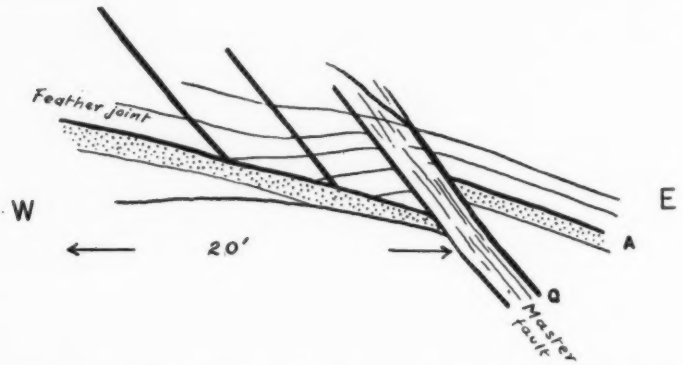

FIG. 10.—Relation between steep-dipping master fault and greatly dipping feather joints. Granodiorite of Big Oak Flat. Legend: *A*, aplite; *Q*, quartz vein.

The phase represented by primary flexures in the granodiorite was a second or third one in the formation of the structure. The movements along the reverse faults of the Mother Lode proper may have occurred before the batholithic invasion. This is indicated in the arrangement of pre-granitic forerunners of the major batholith. The earliest intrusions seem to have been influenced by this zone of weakness during their invasion.

The Mother Lode proper may be older than the structures in the northern and southern portion of the larger zone. Structures in these two regions are closely associated with igneous contacts. Their strike and dip have influenced the Grass Valley, Nevada City, Alleghany, and Ophir veins profoundly. Veins in the Potter Ridge region (south of Mariposa) occur near contacts of wall-rock inclusions. These structures must be closely connected with the intrusive phase. The writer believes they are contemporaneous with marginal

thrusts of the Sierra Nevada batholith. The Mother Lode proper is not only a reverse fault but a narrow and continuous boundary zone. It seems possible that movement along this fault began long before intrusion of the larger batholithic masses.

LATERAL INTRUSIVES

The Sierra-Nevada batholith is a composite igneous mass consisting of a large group of individual intrusions which followed each other at close intervals. The earliest magmas rose along the western contact, or in its neighborhood. These were basic and were followed by acid ones farther to the east. A number of smaller granitic massifs occur west of the main batholith. Their composition is similar to that of the main pluton.

The shape and location of lateral intrusives depend largely on the trend of wall-rock structures. Basic magmas, now represented by large bodies of serpentine, are closely alined with the general trend of the region. The Mother Lode fault is accentuated throughout its entire length by such serpentines. Metadiorites and granodiorites either are alined or else occur in locations where the general strike of the region is distorted and abnormal, as, for example, at Big Oak Flat (Fig. 3) or Mokelumne Hill.

Metadiorites.—Two types of lateral granitic intrusions may be distinguished. The metadiorites, according to Knopf[23] and evidence found by the writer, are of pre-Mariposa age. The situation of these small intrusives was possibly determined by the boundary between the Calaveras sediments and the metavolcanics, their arrangement along this zone being obvious (Fig. 1). Their form and shape are in conformity with the structure of the adjacent Calaveras series. Variations in strike and dip are mostly followed by the intrusive contacts. Tongues of metadiorite extend between the Calaveras beds or schist layers. Wherever the strike swerves into a northeasterly trend the magma follows this direction. Primary structures within these small stocks parallel the contacts and participate in all deviations from the regional trend. The Mother Lode report by Knopf[24] shows seven such metadiorite masses which are located on the boundary between Calaveras schist and the accompanying

[23] *Op. cit.*, p. 18. [24] *Ibid.*

metavolcanics. It seems possible to the writer that this alinement has significant bearing on the structure of the region at the time of the Calaveras deformation.

A connection of the metadiorites with underlying large batholithic masses is nowhere indicated. Internal structures suggest steep contacts and stocklike shape. Downward narrowing was observed, and outward flaring contacts seem absent.

On account of evidence given by Knopf and because of recent structural observations, the writer believes that the metadiorites were intruded at the end of a period of folding and metamorphism which involved the Calaveras series and included volcanics before deposition of the Mariposa series.

Granodiorites.—Post-Mariposa intrusions are abundant and of the same age as the earlier intrusive phases of the main batholith. Since pre-Mariposa metadiorites and post-Mariposa intrusions are not always distinguished in the older maps, their recognition is often impossible without further field examination. Several such intrusions, however, can be seen penetrating the Mariposa slate west of the Mother Lode proper. The masses are very small, and steep contacts indicate stocklike bodies. These western intrusives increase in number and size northward. They are grouped by the writer into a western batholith north of Placerville.

An underground connection between these intrusives and the large Sierra Nevada batholith to the east is held unlikely, because westward dipping contacts, such as would point toward a connection between the larger masses, are lacking in the main batholith. Since these contacts do not transgress the Mother Lode proper, except at one point south of Mariposa, it is assumed that the same persistence holds in depth as in strike.

SUMMARY AND CONCLUSIONS

The writer believes that the larger Mother Lode zone was formed in intimate association with the intrusion of the Sierra Nevada batholith.

A period of intense deformation, accompanied by igneous intrusions, followed the deposition of Calaveras (Carboniferous) sediments. The intrusions assumed an alinement which indicates the later trend of the Mother Lode proper.

Just as the auriferous lodes show a tripartite arrangement (a northern area of numerous, scattered lodes; a medial continuous zone; and a southern barren division), so the internal structure of the batholith reveals from south to north a subdivision into three significant portions: a southern portion which is confidently believed to transgress obliquely the western wall rocks along eastward-dipping contact planes; a central continuous, steep-walled mass; and a northern area of numerous, scattered, and small massifs. The writer is of the opinion that the southern portion of the mass converges downward into a conduit zone, appreciably narrower than the area of surface exposures, that the level of exposure ascends northward, and that in the northern area a shallow level of the batholith is exposed.

A comparison of gold values, produced from mines of the larger Mother Lode zone, indicates an increase from the south toward the north, coinciding with the plunge of the batholith. Mining claims prevail in the southern region, deep rich mines in the north. Even the Mother Lode proper indicates the same coincidence.

The mineralization of this major zone is believed to accompany closely the shallower levels of the batholith, and this principle is thought to explain why the southern portion of the great pluton is almost devoid of gold deposits. Further prospecting may find it advisable to consider this theory.

The age of the mother-lode structures can be placed between the time of the Calaveras intrusives and that of the basic dikes which follow the main batholithic intrusions and transgress the mother-lode structures. The gradually diminishing force or increasing consolidation becomes evident in the small movements which continued into the plastic phase of the batholith intrusion. It seems evident that the lack of continuous mother-lode structure in the southern region is due to the spreading of the batholith and its deeper level of exposure; the uniformity of the Mother Lode proper seems due to the laterally crowding batholith; and the lack of uniformity in the northern region is due to the scattered occurrence of intrusions and to the resistance of the second western batholith. Continuous zones, comparable to the Mother Lode proper, cannot be expected in either the northern or southern regions. Mineralization will probably always be found greatest in the north.

VOLUME, SHAPE, AND ROUNDNESS OF QUARTZ PARTICLES

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ABSTRACT

The article deals with methods of measuring the volume, shape, and roundness of sedimentary quartz particles.

INTRODUCTION

The important properties of sedimentary rock fragments are: (1) the mineralogical and chemical composition; (2) the specific gravity; (3) the volume size or the size of the true nominal diameter; (4) the sedimentological shape and sometimes the crystallographic form; and (5) the roundness of the corners and edges. The regional character of a sediment is indicated by the mineralogical composition and the size of the fragments. The presence of rare and "heavy" minerals may give a clue to the source of the particles, or may be used for correlation of sediments within a given region. The volume size, the specific gravity, and the sedimentological shape are the principal factors governing transportation and deposition, so far as the fragments themselves are concerned. The roundness of the corners and edges may indicate the rigor[1] of the last stage of transportation. Increasing rigor increases fracturing and chipping and reduces the roundness of the corners in general. Rounding of sedimentary fragments is a special type of disintegration attributed to attrition and sometimes to solution. High degree of roundness is often an indication of gentle conditions of wear relative to size, hardness, and toughness of the fragment. Rounding frequently takes place in the bed-load material under gentle tractional transportation. Solution processes in deposited sediments and disintegrated rocks sometimes lead to a relatively higher degree of roundness of the smaller particles

[1] C. K. Wentworth introduced "rigor" as a term for the violence of transportation, in "A Field Study of the Shapes of River Pebbles," *U.S. Geol. Surv. Bull.* 730*C* (1922).

than of the larger ones, which is generally the reverse of what is found in worn sands.[2]

Most of the formulas and terms used in this article have been described and defined in previous papers.[3]

OUTLINE OF THE ANALYSIS

The present research is an attempt to obtain data on the important properties of sedimentary rock fragments, thereby making it possible to group the particles at will on the basis of any specified property. A classification may be made on the basis of the mineralogical composition and the specific gravity of the fragments; each of the obtained classes may be subdivided into volume-classes of proper intervals, and each of the subclasses divided into classes for shape and roundness. By this method, or some variation of it fitted to the purpose of the research, results are obtained which may furnish a clue to the origin of the sediment and to the processes involved in transportation and deposition.

The steps involved in the suggested analysis are illustrated in Table I. The sizes of the class intervals are tentative. The specific gravity classes are suited to the most convenient limits for centrifuge–heavy-liquid separation of quartz from the small amount of non-quartz particles present in St. Peter sandstone.[4] Owing to the

[2] H. C. Sorby, "On the Structure and Origin of Non-calcareous Stratified Rocks," *Quart. Jour. Geol. Soc.*, Vol. XXXVI (1880), Proc., pp. 48–92.

[3] Hakon Wadell, "Volume, Shape and Roundness of Rock Particles," *Jour. Geol.*, Vol. XL (1932), pp. 443–51; "Sphericity and Roundness of Rock Particles," *Ibid.*, Vol. XLI (1933), pp. 310–31; "The Coefficient of Resistance as a Function of Reynolds Number for Solids of Various Shapes," *Jour. Franklin Institute*, Vol. CCXVII (1934), pp. 459–90; "Shape Determinations of Large Sedimental Rock-Fragments," *Pan-American Geologist*, Vol. LXI (1934), pp. 187–220 (Unfortunately several misprints occur in this paper. The integration symbol, $\int$, is used throughout the paper instead of f as symbol for function. Equation (8) on page 203 should read: $\Psi = (d_n/D_s) + 0.1$.); "Some New Sedimentation Formulas," *Physics*, Vol. V (1934), pp. 281–91.

[4] The presence of non-quartz minerals, the specific gravity of which overlaps that of quartz within the class limits given in Table I, does not impair the final result, although the centrifuge–heavy-liquid separation of quartz from the small amount of non-quartz particles of about the same specific gravity may not be satisfactorily accomplished. Only quartz particles were reproduced in the subsequent drawing of the grains under the microscope.

fact that practically nothing is known in respect to the influence of the grain shape on the result of the sifting process, it has been difficult to decide upon the size of the volume-classes. Although an attempt has been made to reduce the "error" due to the particle shape, it is not yet certain how far this correction has been accomplished. The aim has been to obtain purely dimensional size values, without the influence of shape. The volume-classes should not be too large, yet large enough to reduce the influence of the grain shape to a minimum. The number of particles improperly classified (owing to the influence of shape on size determination) has less influence on the structure of the statistical particle distribution when large volume-classes are used, because the number of fragments correctly allotted to a class of given limits increases with increasing size of the class intervals, while the influence of shape on the size determination of the particles is felt only in the immediate vicinity of the class boundaries by relatively few overlapping fragments, compared with the greater number of particles of the entire class. The class limits for sphericity and roundness have been determined by increasing the size of the classes until the column diagram, on the basis of the given number of investigated particles, showed an orderly distribution and "smooth" outline without any excessively irregular structure. In conclusion, Table I illustrates only the general outline of the analysis. It is believed that the size of the class intervals can be further reduced by improved technique in determining the properties, whereby finer variations in the particle distribution may be detected.

INSTRUMENTS AND APPARATUS

The following equipment was used for the present study of sand grains: (1) a Ro-tap testing sieve shaker from W. S. Tyler Co., Cleveland; (2) four testing sieves with openings in millimeters as follows: 0.500, 0.250, 0.125, 0.061, and pan; (3) an E. Leitz's microscope CM and accessories, including an ocular No. 3 and three achromatic objectives, No. 6 (4 mm.), No. 3 (16 mm.), and No. 1 (40 mm.); (4) a mechanical stage; (5) an object-micrometer scale of 5 mm. in tenths; (6) a camera lucida; (7) a polar planimeter from Keuffel and Esser Co.; (8) a circle scale (Fig. 1), consisting of a number of circles drawn on the ground surface of a 20×20-cm. sheet of trans-

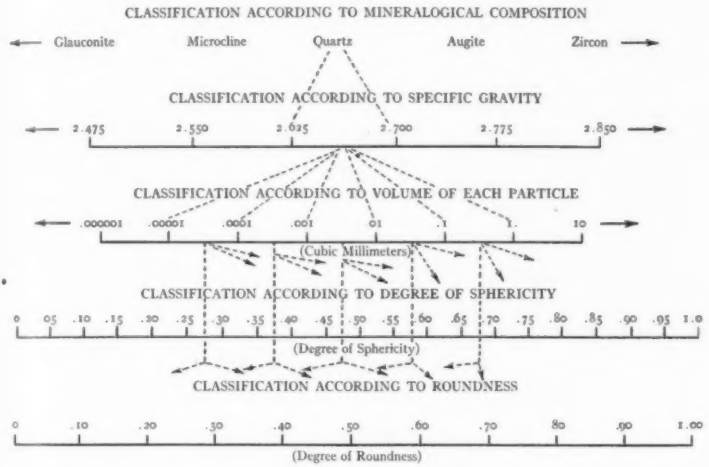
parent celluloid of the kind used for photographic cut-film.[5] The innermost circle of 1 mm. radius was drawn in black (India ink); the next five circles of 2, 4, 6, 8, and 10 mm. radii in red (India ink); the following five circles of 12–20 mm. radii in black; and so forth up to the outermost circle of 70 mm. radius. The alternation of colors in

TABLE I

TEST SAMPLE
(116 Grams)

Analysis of 1,000,000 Grains

(Distribution of the Particles according to their Mineralogical Composition and Physical Properties)



sets of five circles (10 mm.) facilitates the reading of the radius. (9) A centrifuge apparatus for mineral separation in heavy liquids; (10) a balance having a sensitiveness of 0.1 mg.; and (11) calculating machines.

PREPARATION OF THE SAMPLE FOR ANALYSIS

For this advance in an almost unknown field, it was deemed desirable to choose a sediment composed entirely, or almost entirely,

[5] Celluloid of this kind may be purchased in any well-stocked shop carrying drawing material. It may also be obtained by boiling a large photographic cut-film in water for a minute or two, thereby removing the gelatinous coat.

of particles of the same specific gravity, thereby avoiding separate analysis of particles of different specific gravities. Through the courtesy of Dr. F. J. Pettijohn a sample of St. Peter sandstone was supplied from the collection of the sedimentological laboratory of

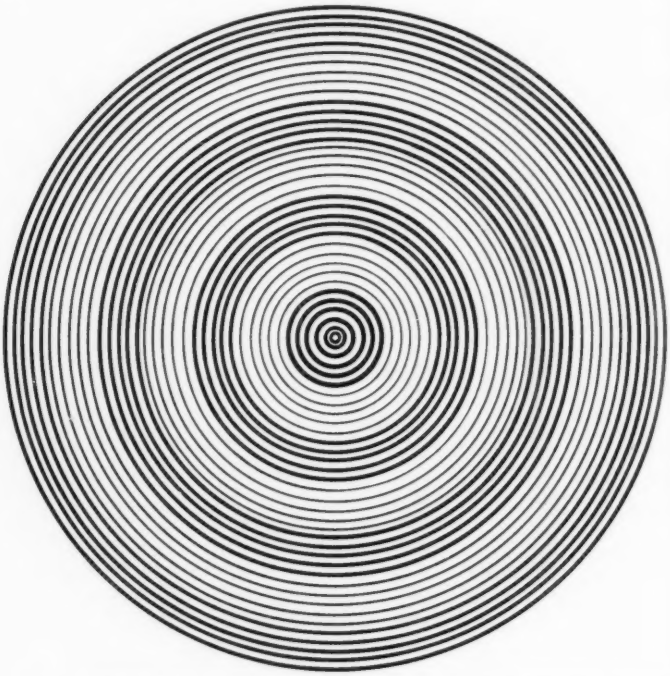


FIG. 1.—Circle-scale of 2 mm. intervals, except for the two innermost circles of 1 and 2 mm. radii. (Reproduced for illustration only, not for accuracy.)

the University of Chicago. It is believed that owing to the generally recognized homogeneity of St. Peter sandstone the sample may be considered to represent the composition of the sandstone in the immediate surroundings of the sample locality. The sample was collected near the base of St. Peter sandstone in Utica Township, T. 33 N., R. 2 E., Sec. 7, where the road crosses Pecumsaugan Creek approximately 3 miles northeast of La Salle, Illinois.

The sample was "cut down" for screen analysis to about 116 grams. The few mineral particles heavier and lighter than quartz were removed in bromoform by centrifuge, and the remaining quartz grains shaken for 15 minutes in a Ro-tap testing sieve shaker. The result of the screen analysis is given in Table II, second and third columns from the left.

The material retained on each sieve was further "cut down" by quartering to a weighable amount small enough to be spread over a

TABLE II

Screen Openings in Mm.	Weight of Material in Mg. on Each Sieve	Number of Grains Present on Each Sieve	Number of Grains per Million	Frequency Value of Each Investigated Grain (F)
0.500	187.2	650	95	3
0.250	61321.4	937,636	136,340	2,726
0.125	49192.8	3,652,027	531,038	10,620
0.061	5446.6	1,876,843	272,909	5,458
Pan	101.9	410,000	59,618	1,192
Total	116,249.9	6,877,156	1,000,000	

microscopic slide. The grains on each slide (each grade size) were counted under the microscope, using a mechanical stage. Knowing the number of grains present on a slide and their total weight, the number of grains retained on the sieve was computed on the basis of the weight of the sieve material. The results are given in Table II, third column. The fourth column gives the computed number of grains per million.

Each slide was then treated as follows: The sand grains were thoroughly mixed, and one-half to three-fourths of the amount removed after careful quartering. The remaining particles were spread over an area about equal to the size of a cover glass. The slide was given a few gentle taps with a pencil so that all particles came to a stable rest on one of their larger surfaces, more or less parallel to the largest and intermediate diameters.[6] To raise the relief a few drops

[6] The weakest part of an irregular quartz grain is, as a rule, along the direction of its smallest diameter. The results of fracturing, chipping, attrition, and solution of the particles are therefore most noticeable at right angles to the shortest diameter, i.e., in the plane of the longest and intermediate diameters.

of clove oil ($n = 1.560$) were added, and a cover glass very gently placed on top. The slide was then ready for reproduction.

REPRODUCTION OF THE SAND GRAINS TO THE STANDARD SIZE

The reader will recall from discussions in previous papers that the measurement of the roundness requires a reproduction of the grains in the "standard size." Large objects, such as boulders, must be reduced, and small ones, like sand grains, magnified to approximately the same size, i.e., the "standard size," on which the roundness measurements are performed. The average diameter of the reproduced grains in the standard size has been fixed at about 7 cm., and quartz particles were given a linear enlargement to about that size by camera lucida.

The standard size was obtained by use of the proper objective for each grade size, and by regulating the distance between the camera lucida mirror and the drawing paper. Thus the particles of the pan and of the 0.061-mm. sieve were given a 600× linear enlargement; those of the 0.125-mm. sieve, a 213× enlargement, and the grains of the 0.250-mm. and 0.500-mm. sieves, a 143× linear enlargement. The magnifications were measured by means of an object-micrometer scale of 5 mm. in tenths, the latter being reproduced in the center of the microscopic field and by means of the camera lucida drawn on the paper. The scale reproduced on the paper was measured with a ruler, and the amount of linear magnification computed. The values for the enlargements thus obtained are sufficiently accurate for the purpose of the investigation. The average maximum diameter of the grain reproductions amounted to about 7 cm., i.e., the standard size. The proper distance between the camera lucida mirror and the drawing paper was determined for a given slide by one of the largest grains present on the slide, in order that no grain, when reproduced to the standard size, would occupy more than one-third of the microscopic field. For reproduction each particle was placed in the center of the field.[7]

[7] No attempt should be made to draw a particle which is not in the center of the field. The distortion in the outer parts of the microscopic field is so great, especially with high-power objectives, that a reasonably accurate outline of the particle is not obtained if the grain occupies more than one-third of the field.

The drawing of the larger grains sometimes required a slight adjustment of the focus for the individual grains, in order to bring out a sharp maximum border line. Whenever the curvature of a corner could be followed inside the maximum outline of the particle, its continuation was traced on the paper, (Fig. 2*a*). All grains showing signs of secondary crystal growth were omitted.

In order to secure a representative result and to avoid error from uneven grain distribution on the slide, the following rule was carried

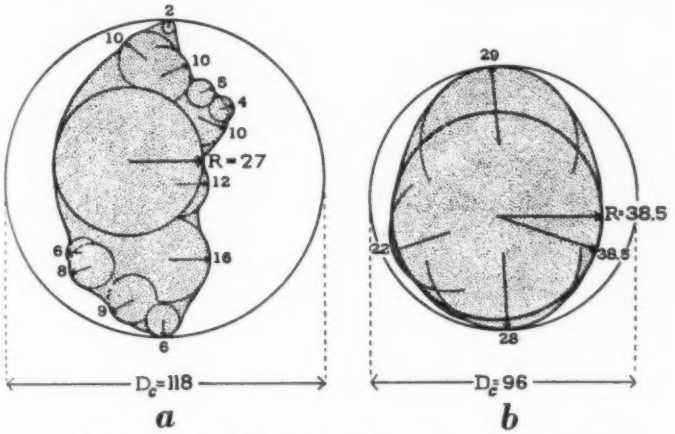


FIG. 2.—Camera lucida drawings, *a*, of a grain retained on the 0.125-mm. sieve, *b*, of a grain retained on the 0.061-mm. sieve. (The figures give the dimensions in millimeters.)

out. Starting with the easternmost grain on the slide, all particles falling on the east-west cross-hair were reproduced as the microscopic view was changed along a straight east-west line by means of the microscopic stage. Then the northernmost grain was used as a starting-point, proceeding in the same way but in a north-south direction, avoiding drawing any grain previously reproduced along the east-west line. If the number of particles thus sketched was not sufficient, the reproduction was continued along some line parallel to those previously used.

Two hundred and twenty-five particles were drawn, 50 of each grade size (of each slide), except for the grains of the 0.500 mm.

sieve, where 25 particles were deemed sufficient to represent the small amount present. The variation in size, shape, and roundness of the grains of each grade size is not likely to be so great that 50 particles will not give a representative picture of the grain properties. It is recommended for the future, however, to choose the number of grains proportionate to the number of particles on the sieve, instead of choosing the same number for all screens as, with one exception, was done in the present study. But not less than 20 particles should be reproduced in any given grade size.

The preceding sections have described the operations leading up to and including the reproduction of sand grains to the standard size. This concludes the mechanical part of the analysis; what follows treats of the methods of computing the sedimentary properties from measurements obtained on the reproductions.

VOLUME, WEIGHT, AND NOMINAL SECTIONAL DIAMETER OF A QUARTZ PARTICLE

The size of a non-spherical particle can be computed with fair accuracy on the basis of the sedimentation velocity within the region of Stokes' law,[8] The use of sieves in mechanical analysis has, however, the advantage of speed. A serious difficulty in connection with screen analysis arises from the fact that the "three diameters" of a sedimentary particle are rarely equal, there usually being a largest, a least, and an intermediate diameter, the last of which ordinarily determines whether the grain will pass the sieve. An accurate size analysis by screening can therefore be achieved only when all particles have the same geometric form. Since this is never the case, there is always an "error" involved, owing to varying non-spherical shapes of the particles. In the present study an attempt has been made to reduce this error somewhat by computing the true nominal diameter from measurements obtained on the reproductions. The diameter and the radius of a sphere of the same volume as a given spherical or non-spherical solid have been previously introduced as the true nominal diameter and the true nominal radius, respectively. "Nominal sectional diameter" is here introduced as a term for the diameter of a circle equal in size to the area of the non-magnified reproduction

[8] Wadell, "Some New Sedimentation Formulas," *loc. cit.*

of a quartz particle in the plane of the largest and intermediate diameters. Our aim is to show that the true nominal diameter can be computed, without too great error, from the nominal sectional diameter obtained and computed from the grain projection in the standard size. The nominal sectional diameter is computed as follows.

Figure 2*a* represents the standard size or the magnified projection of a grain retained on the 0.125-mm. sieve. The area of the original grain reproduction (not of the size given in Fig. 2*a*) as measured by a polar planimeter on the standard size amounted to 5,120 sq. mm., corresponding to a circle area of an 80.7 mm. diameter. Since the grains of the 0.125-mm. sieve had been given a linear magnification of 213×, the value of the nominal sectional diameter, d_{cn}, of the grain amounts to

$$d_{cn}=\frac{80.7}{213}=0.3788 \text{ mm.} \tag{1}$$

The following is intended to show that the nominal sectional diameter, d_{cn}, as computed above, does not deviate excessively from the value of the true nominal diameter, d_n, the latter being a purely dimensional size value by which the volume can be computed.

The nominal sectional diameter of a spherical grain equals the true nominal diameter of the sphere. Thus the volume of a perfect sphere can be computed by the formulas:

$$V_s=\frac{\pi}{6}\cdot d_{cn}^3\,;\; V_s=0.5236\cdot d_{cn}^3\,, \tag{2}$$

where V_s is the volume of the sphere and d_{cn} the nominal sectional diameter.

Assuming that all particles retained on a sieve are spherical, their total volume, V_t, may be obtained approximately by multiplying the arithmetic mean of the volumes of the investigated particles (the volume of each particle computed in the manner demonstrated by Formulas (1) and (2)) by the total number of grains present on the sieve. Thus expressed:

$$V_t=N\cdot\frac{0.5236(\Sigma d_{cn}^3)}{N_i}\,, \tag{3}$$

where V_c is the total volume of the grains as computed by Formula (3), N the total number of particles present on the sieve and computed in a manner previously demonstrated (Table II), N_i the number of investigated particles, reproduced and measured, and Σd_{cn}^3 the sum of the cubes of the nominal diameters, d_{cn}, of the investigated grains.

The total weight, W_c, of the grains is obtained by multiplying their total volume, V_c, by their specific gravity, ρ_s.

$$W_c = V_c \cdot \rho_s . \tag{4}$$

It has been found that the computed weight, W_c, generally approaches the value of the actual weight, W_a, obtained by direct weighing of the particles.

When dealing with grains of non-spherical shape, the difference between W_c and W_a increases with departure from spherical shape, and especially with increasing flatness of the particles. This difference computed as percentage of the actual weight, W_a, expresses also the difference between the actual and computed average grain volume. The particles retained on the 0.250-mm. screen are chosen as an example. The values used for the calculation are found in Tables II and III.

$W_a = 61321.4$ mg. = the actual weight of the grains retained on the 0.250-mm. sieve.

$N = 937{,}636$ = the total number of grains retained on the 0.250-mm. sieve.

$N_i = 50$ = the number of investigated grains of 0.250-mm. sieve.

$\rho_s = 2.65$ = the specific gravity of quartz.

$\Sigma d_{cn}^3 = 2.469847$ = the sum of the cubes of the nominal sectional diameters of 50 investigated grains. The numerical values of the nominal sectional diameters (not their cubes) are given in the column marked d_{cn} of Table III.

Applying Formulas (3) and (4) and substituting the numerical values above, the computed weight, W_c, amounts to:

$$W_c = 937{,}636 \cdot \frac{0.5236\ (2.469847)}{50} \cdot 2.65 = 64259.3 \text{ mg.} \tag{5}$$

TABLE III

NUMERICAL VALUES OF ROUNDNESS, SPHERICITY, AND NOMINAL DIAMETER OF FIFTY INVESTIGATED QUARTZ PARTICLES OF THE 0.250-MM. SIEVE

No.	P	ϕ	d_{en}
1	0.546	0.694	0.3103
2	0.540	0.925	0.4007
3	0.529	0.877	0.5262
4	0.523	0.877	0.3516
5	0.520	0.769	0.1733
6	0.520	0.813	0.3470
7	0.507	0.970	0.3248
8	0.497	0.847	0.2603
9	0.483	0.746	0.3556
10	0.471	0.719	0.4440
11	0.469	0.847	0.3804
12	0.467	0.819	0.2992
13	0.465	0.819	0.2985
14	0.452	0.763	0.3470
15	0.438	0.746	0.2557
16	0.421	0.917	0.3890
17	0.413	0.862	0.2902
18	0.408	0.813	0.3573
19	0.392	0.917	0.3206
20	0.383	0.869	0.3117
21	0.380	0.847	0.2724
22	0.377	0.833	0.3046
23	0.375	0.847	0.5911
24	0.344	0.869	0.4069
25	0.338	0.793	0.2445
26	0.337	0.909	0.4390
27	0.327	0.909	0.3040
28	0.325	0.833	0.3880
29	0.315	0.943	0.3694
30	0.307	0.862	0.3486
31	0.304	0.671	0.4262
32	0.303	0.781	0.3881
33	0.298	0.793	0.3545
34	0.296	0.877	0.3440
35	0.287	0.833	0.3838
36	0.256	0.751	0.3206
37	0.253	0.793	0.3230
38	0.251	0.806	0.3666
39	0.246	0.840	0.3248
40	0.244	0.833	0.5082
41	0.236	0.877	0.3429
42	0.223	0.869	0.3103
43	0.220	0.877	0.4470
44	0.209	0.746	0.2916
45	0.206	0.806	0.3374
46	0.201	0.840	0.3353
47	0.195	0.735	0.2882
48	0.157	0.854	0.3103
49	0.152	0.806	0.3389
50	0.100	0.840	0.3644

The difference between W_c and W_a expressed as percentage of W_a is obtained by the formula:

$$\frac{100\,(W_c - W_a)}{W_a}\,; \tag{6}$$

or substituting the numerical values:

$$\frac{100\,(64259.3 - 61321.4)}{61321.4} = 4.7 \text{ per cent}\,. \tag{7}$$

Since the specific gravity value, 2.65, enters both W_c and W_a, the result, 4.7 per cent, expresses also the difference between the actual and computed average grain volume. Table IV gives the results obtained by similar calculations for the particles of the four sieves and the pan.

TABLE IV

Sieve (Mm.)	$\frac{100(W_c - W_a)}{W_a}$ (Percentage)	Percentage Difference in Respect to Diameter
0.500	8.3	2.7
0.250	4.7	1.5
0.125	37.5	11.2
0.061	10.8	3.4
Pan	51.2	14.7

The high percentage, 51.2, on the pan is probably due to the fact that (1) the very finest grains of a nominal sectional diameter less than 0.04 mm. were omitted in drawing, because their magnification to the standard size would have involved an extra arrangement which was deemed unnecessary, since their total weight amounted to an extremely small fraction of 1 per cent of the whole sample of St. Peter sandstone; and (2) these particles had in general a somewhat more flaky form than the grains of the sieves. The 37.5 per cent obtained for the 0.125-mm. sieve appears abnormally high in view of the low values for the screens above and below. It suggests that the 50 investigated particles are not representative of the entire amount

of 3,652,027 particles retained on that sieve, at least not so far as the particle size is concerned. They may, however, be adequate in respect to sphericity and roundness, because these properties are not necessarily subject to the same amount of variation as the particle size. The percentages 8.3, 4.7, and 10.8 for the remaining screens (0.500 mm., 0.250 mm., and 0.061 mm.) can be regarded as reasonably satisfactory. It should be noted that the percentage values express the difference in volume and not in diameter, which is the common basis for size classification. Since the diameter of a sphere equals $\sqrt[3]{\text{Volume}/0.5236}$, the percentage values in respect to the difference in diameters are less conspicuous (Table IV). Even as much as 51.2 per cent difference in volume between two spheres, figured as percentage of the smaller sphere, amounts only to 14.7 per cent when computed on the basis of the diameter values of corresponding spheres. Although the last figure (14.7) is rather high, it compares favorably with many values obtained by various proposed methods and computed from linear measurements of more or less arbitrary diameters in one plane of a non-spherical quartz particle.

In conclusion, the advantages of the nominal sectional diameter are: (1) that its numerical value gives a good average of all diameters in the plane of measurement; (2) that personal opinion in choice of diameters for measurement is avoided; (3) that, whereas many proposed methods, such as the measurement of the "statistical diameter,"[9] give an average size value of a great number of particles, the nominal sectional diameter is a permissible size expression for a single quartz grain; and (4) that the accuracy of the nominal sectional diameter as a size value increases with increasing degree of true sphericity, and, when dealing with perfect spheres, the nominal sectional diameter equals the true nominal diameter, which latter equals the diameter of the sphere. Since quartz has no pronounced cleavage, it is not likely that fracturing and chipping in sedimentary transportation will produce very flat quartz particles; consequently the nominal sectional diameter of a sedimentary quartz grain may generally be used as a size value of fair accuracy.

[9] Geoffrey Martin, "Law Governing the Connection between the Number of Particles and Their Diameters in Grinding Crushed Sand," *Trans. Ceramic Soc.*, Vol. XXIII (1923–24), pp. 61–120.

SPHERICITY AND ROUNDNESS MEASUREMENTS

It has been shown by the coefficient of resistance, as a function of Reynolds number for solids of various shapes, that the sedimentological form, bearing approximately on the terminal uniform settling velocity of solids, can be expressed by the ratio:[10]

$$\frac{s}{S}=\psi\,, \tag{8}$$

where s is the surface area of a sphere of the same volume as the solid, S the actual surface area of the solid, and ψ denotes the degree of true sphericity. The maximum value obtained for ψ is 1, which is the numerical shape value of a sphere.

There are several rather accurate methods for surface determination of small particles in bulk. None of these could, however, be adopted for the present study, because it was desirable for classification in the statistical charts to obtain a sphericity value for each particle rather than bulk values for a great number of granules. Lack of experimental data has made it necessary to adopt the same scheme used in a previous paper dealing with shape determination of larger rock fragments.[11] Table V gives the dimensions of five geometric forms, the same used as prototypes in the earlier paper. Figure 3 illustrates the outline of the same solids as they would appear under the microscope, when they rest on one of their largest faces, more or less parallel with the largest cross-sectional area. It is assumed, for obvious reasons, that the cube rests on one of its square faces, while the other parallelopipeds rest on one of their two larger rectangular faces. It is recalled that the sand grains for reproduction were placed in their most stable position of rest by a few gentle taps on the slide.

A practical formula for computing the shape of a quartz grain must be such that the obtained value approaches as closely as possible the degree of true sphericity. The following formula is suggested:

$$\frac{d_c}{D_c}=\phi\,, \tag{9}$$

[10] Wadell, "The Coefficient of Resistance as a Function of Reynolds Number for Solids of Various Shapes," *loc. cit.*; "Shape Determinations of Large Sedimental Rock-Fragments," *loc. cit.*; "Some New Sedimentation Formulas," *loc. cit.*

[11] Wadell, "Shape Determinations of Large Sedimental Rock-Fragments," *loc. cit.*

where d_e is the diameter of a circle equal in area to the area obtained in the standard size when the grain rests on one of its larger faces, more or less parallel to the plane of the longest and intermediate diameters, and D_e is the diameter of the smallest circle circumscribing the grain reproduction of the standard size. The shape value achieved by this method is denoted by the Greek letter ϕ. It is assumed that the ϕ-value generally approaches the ψ-value, i.e., the value of the degree of true sphericity (Formula (8)).

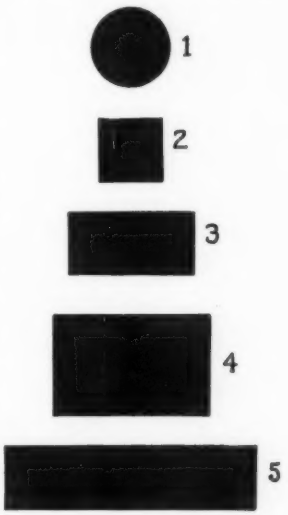


FIG. 3.—Outlines of five geometric prototypes in their most stable position of rest.

Table V gives the ϕ- and ψ-values for the five geometric prototypes. The ϕ-value is computed according to Formula (9) and on the basis of d_e being the diameter of a circle area equal to the projection area (Fig. 3) and D_e being the diameter of the smallest circle circumscribing the projection area. An inspection of Table V shows that for spheres $\psi = \phi$. For the other forms the value of ϕ approaches that of ψ, except for parallelopiped No. 4, which is a very flat and rather square-shaped solid. It is especially to be noted that the table is not intended to mask the actual situation. For other geometric forms the difference between the ϕ- and ψ-values may take other proportions. For instance, a circular disc obtains a maximum ϕ-value, i.e., 1, while its actual ψ-value may be very low. Quartz particles, however, do not in general attain very flat shapes, and sedimentary quartz grains of circular disc shape may be considered as extremely rare. Very thin quartz particles of a size larger than 0.1 mm. are readily broken up into several pieces by tractional transportation, each fragment attaining a higher degree of true sphericity (ψ) than the original particle of the same thickness. Irregularly shaped sedimentary quartz may well have rather thin edges, but the thickness

generally increases toward the center, thereby increasing the degree of true sphericity. In conclusion, it is believed that the ϕ-value in general approaches the actual ψ-value without excessive deviation. It has also been shown in a previous paper[12] that similar formulas, constructed for larger rock fragments on the basis of the same prototypes presented above, agreed reasonably well with experimental data bearing on the sedimentation velocity and the coefficient of resistance as a function of Reynolds number.

TABLE V

DIFFERENCE BETWEEN THE ψ- AND ϕ-VALUES FOR FIVE GEOMETRIC FORMS

No.	Geometric Form	Dimensions	Volume	ψ	ϕ	$\phi - \psi$
1	Sphere	Diam. 2.48	8	1.00	1.00	0.00
2	Cube	2×2×2	8	0.80	0.79	−0.01
3	Parallelopiped	4×2×1	8	0.69	0.71	0.02
4	Parallelopiped	5×3.2×0.5	8	0.48	0.75	0.27
5	Parallelopiped	8×2×0.5	8	0.46	0.54	0.08

Roundness has been discussed in two previous papers.[13] The arguments presented tended to show that the degree of roundness is essentially a planimetric conception, referring to the smooth curvature of the outline of a plane area, projection area, or cross section. A "plane corner" was defined as every such part of the smooth outline which has a radius of curvature equal to or less than the radius of the maximum inscribed circle in the given area. Thus a plane corner has reached its maximum degree of roundness when the radius of its smooth curvature equals the radius of the maximum inscribed circle. The total roundness of a solid may be obtained by curvature measurements in several cross-sectional planes, but one plane is generally satisfactory when dealing with sedimentary sand grains (see footnote 6).

The roundness of a plane corner is expressed by the ratio r/R, where r is the radius of curvature of the corner, and R is the radius of

[12] Wadell, "Shape Determinations of Large Sedimental Rock-Fragments," *loc. cit.*

[13] Wadell, "Volume, Shape and Roundness of Rock Particles," *loc. cit.*; "Sphericity and Roundness of Rock Particles," *loc. cit.*

the maximum inscribed circle, both values obtained by measurements on the standard size. The maximum value for r/R is 1.00 for a corner (hereafter always understood to be a plane corner if not otherwise specified) of maximum roundness. The total roundness in one plane equals the arithmetic mean of the roundness values of the corners, thus:

$$\frac{\sum\left(\frac{r}{R}\right)}{N}=\mathrm{P}\,, \tag{10}$$

where $\sum\left(\frac{r}{R}\right)$ is the sum of the roundness values of the corners, N the number of corners in the given plane, and P denotes the total degree of roundness. The maximum value obtained by this formula is 1.000 for a particle of maximum roundness in the given cross section or projection plane.

A formula which sometimes gives a slightly different roundness value from that obtained by equation (10) has been used in this study. It reads:

$$\frac{N}{\sum\left(\frac{R}{r}\right)}=\mathrm{P}. \tag{11}$$

The maximum value achieved by this formula is also 1.000 for a solid of maximum roundness in the plane of measurement. Preference is given Formula (11), because it results in a slightly lower value for the roundness of particles having corners of greatly different roundness values, i.e., when the coefficient of variation of the roundness values is high.[14] Relatively well-rounded particles, which, by chipping or fracturing shortly before deposition, have obtained a very low degree of roundness for one or more corners, are generally placed in a lower roundness class by use of Formula (11) instead of Formula

[14] The coefficient of variation as developed by Pearson is the standard deviation as percentage of the arithmetic mean, thus

$$C_v=\frac{\sigma}{M_a}\times 100\,,$$

where C_v is the coefficient of variation, σ the standard deviation, and M_a the arithmetic mean of a given number of variables.

(10). The resulting diagram (by use of Formula (11)) is therefore more influenced by recent events of transportation preceding the deposition.

The roundness of a quartz particle was obtained by the following method. We assume that the grain has been drawn on a paper and that the reproduction represents the standard size of the particle in the plane of the longest and intermediate diameters (Fig. 2). All corners, i.e., curves of the outline of the reproduction having a radius equal to or less than the radius of the maximum inscribed circle, are measured. The radius of curvature of each corner is obtained by placing the transparent celluloid circle-scale (Fig. 1) over the drawing and adjusting its circles to the outline of the reproduction so as to obtain a direct reading of the radius of curvature of a given corner. The circle-scale is adjusted so that one of its circles covers as much as possible of the outline of the given corner. The radius of that circle is then taken as the radius of curvature of the corner. The outline of a corner having a radius of curvature of odd value (5 mm., 11 mm., 13 mm., etc.) appears as a curved line between and parallel with two circles of the scale, the latter having circles with 2 mm. intervals. The radius of curvature for such a corner is, of course, given an odd value. Although the circle-scale allows readings to half a millimeter, it is in general found satisfactory to express the radii values of the corners in whole millimeters, because one may always count on a certain amount of error due to inaccuracy of drawing. Curvatures of a radius less than 1 mm. are beyond accurate measuring, and they are therefore always given a radius value of 0.5 mm. The radius of the maximum circle which can be inscribed within the boundaries of the grain reproduction is readily obtained by placing the circle scale over the drawing.

The following illustrates the computation of sphericity and roundness on the basis of the values obtained by the method outlined above. Figures 2*a* and *b* represent the standard size of two grains of the 0.125-mm. and 0.061-mm. sieves, respectively. Figure 2*a*, which illustrates the only quartz particle having as many as twelve corners, has been chosen as an example of what may be expected in an extreme case. Figure 2*b* illustrates the normal appearance of a particle of high sphericity and high roundness.

Example: Figure 2a representing the standard size of a quartz grain of grade size 0.125 mm.

The area of the grain reproduction = 5,120 sq. mm.

d_c = 80.7 mm. = the diameter of a circle area of 5,120 sq. mm.

D_c = 118.0 mm. = the diameter of the circumscribing circle.

Applying Formula No. 9 and substituting the numerical values above:

$$\text{Sphericity } (\phi) = \frac{80.7}{118} = 0.68 .$$

R = 27 mm. = the radius of the maximum inscribed circle.

r = the radius of curvature of a corner. The values for r are shown in Figure 2a and in the table below.

N = 12 = the number of corners in Figure 2a.

$\sum\left(\frac{R}{r}\right) = 53.06$ (see table below).

Applying Formula (11) and substituting the numerical values above:

$$\text{Degree of roundness (P)} = \frac{12}{53.06} = 0.22.$$

r	$\frac{R}{r}$
2	13.50
10	2.70
5	5.40
4	6.75
10	2.70
12	2.25
16	1.68
6	4.50
9	3.00
8	3.38
6	4.50
10	2.70
	53.06

About 70 per cent of all particles were found to have six to seven corners, and only one grain as many as twelve (Fig. 2a). The average number of corners suggests an influence of the crystallographic form of quartz.

GRAPHIC PRESENTATION OF THE RESULT

Table II gives the number of particles per million, computed from the number of particles present on each sieve. Since 50 grains of

each grade size (except for the 0.500-mm. screen where 25 particles were deemed sufficient) were drawn and measured, each investigated grain represented $\frac{1}{50}$ (and $\frac{1}{25}$) of the number of grains per million present in respective grade sizes. Thus screen 0.250 mm. contained 937,636 particles, corresponding to 136,340 grains per million of the total sample of St. Peter sandstone. Each one of the 50 investigated particles represented consequently $\frac{136{,}340}{50} = 2{,}726$ grains per million. The last value, 2,726, is called the frequency value (F) of the investigated particle.

By summarizing the frequency values of grains having the same class characteristics, the total number of particles per million falling in a given class is obtained. Assuming that three particles of the total number of investigated grains attain the sphericity values 0.91, 0.93, and 0.94, they all fall in the same class, 0.90–0.95. For the purpose of illustration assume further, as an extreme case, that the three particles belong to the 0.250-mm., 0.125-mm., and 0.061-mm. sieves, the investigated grains of which have the frequency values 2,726, 10,620, and 5,458, respectively. The total number of grains per million in sphericity class 0.90–0.95 will then be: $2{,}726 + 10{,}620 + 5{,}458 = 18{,}804$ (example only).

The frequency values have the advantage that they permit manipulation and classification of the particles according to any grain property and scheme suited to the investigation and the purpose of the research.

The dotted lines of Table I show how the analysis of the St. Peter sandstone branches out so as to comprise the essential sedimentary properties of the grains. Figures 4, 5, and 6 illustrate the results of the analysis. The particles have been classified according to their properties, and the number of grains of a given class computed on the basis of the frequency values of the investigated particles. Each diagram shows the distribution of one million grains. Particles having property values falling exactly on a class limit were allotted to the class of lower value, because it has been previously shown that the values obtained by the practical formulas for computing the volume and sphericity (ϕ) were slightly too high.

Figure 4 illustrates the distribution of one million grains classified in five volume-classes. The volume of each investigated particle has been calculated according to Formula (2) and on the basis of the nominal sectional diameter, computed in a manner demonstrated by Formula (1). In practice, however, a simpler method has been followed in distribution of the particles in the proper volume-classes.

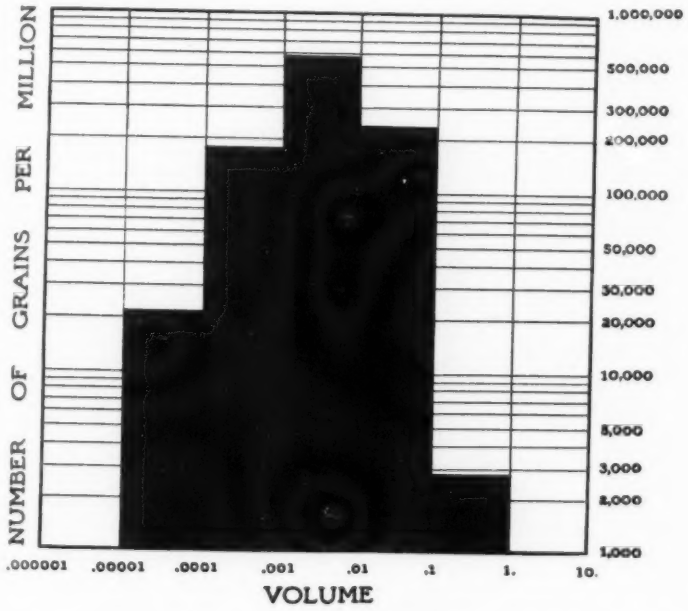


FIG. 4.—Distribution of one million grains classified according to volume (semi-logarithmic scale).

The values of the nominal diameters corresponding to the limits of the volume-classes were computed, and the grains were then allotted directly to the proper volume-classes on the basis of their nominal sectional diameters, without the elaborate work of first computing the volume of each investigated particle. The volume-classes 0.00001–0.0001, 0.0001–0.001, 0.001–0.01, 0.01–0.1, 0.1–1.0, cubic

mm. have the following limits, expressed as diameters of spheres of respective volumes, 0.02673–0.05758, 0.05758–0.12407, 0.12407–0.2673, 0.2673–0.5758, 0.5758–1.2407, mm.

Figure 5 illustrates the distribution of one million grains over the five volume-classes, the grains of each volume-class being classified according to their ϕ-values. Because of the difficulty in expressing adequately the small number of particles in the highest and lowest volume-classes, italic figures have been inserted to indicate the exact amount in each ϕ-class.

Figure 6 illustrates the distribution of one million grains classified according to volume and P-values. The volume-classes 0.01–0.1 and 0.1–1.0 have been united into one, on account of the few particles present in the uppermost class. The same has been done in respect to the two lowest volume-classes. The structure of the entire diagram becomes thereby more pronounced, and variations in roundness may be better visualized.

Arithmetic scales are used in Figures 5 and 6. In order to avoid an unduly large diagram, Figure 4 has been constructed on the semilogarithmic scale.

AVERAGE VALUES FOR SPHERICITY AND ROUNDNESS OF PARTICLES ON EACH SIEVE

Lamar[15] has constructed a mechanical device for determining the "roundness" or "angularity"[16] of sand grains in bulk. The *modus operandi* was as follows.

About 60 cc. of sand, carefully screened to a given sieve size and dried at 100°C., were placed in a cylinder. A downward concentration of the sand was produced by a motor-driven plunger, which raised and dropped the cylinder about half an inch at the rate of 100 times a minute. The cylinder struck on a piece of felt, thus reducing the amount of rebound imparted to the sand. The operation was continued until the volume of sand in the cylinder could be reduced

[15] J. E. Lamar, "Geology and Economic Resources of the St. Peter Sandstone of Illinois," *Ill. Geol. Surv. Bull. 53* (1927).

[16] Lamar's terms "roundness" and "angularity" are practically synonymous with the "sedimentological shape" or the "degree of true sphericity" as used in the present paper.

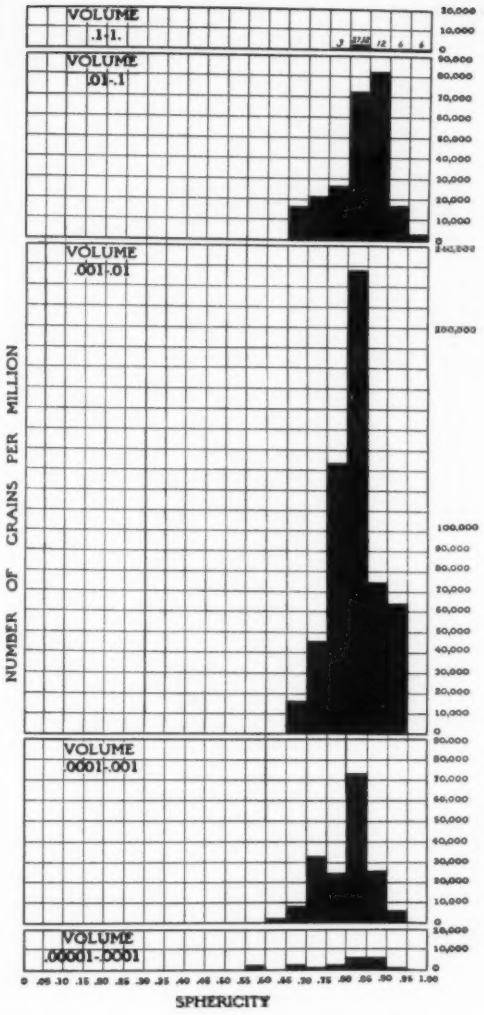


FIG. 5.—Distribution of one million grains classified according to volume and ϕ-value (arithmetic scale).

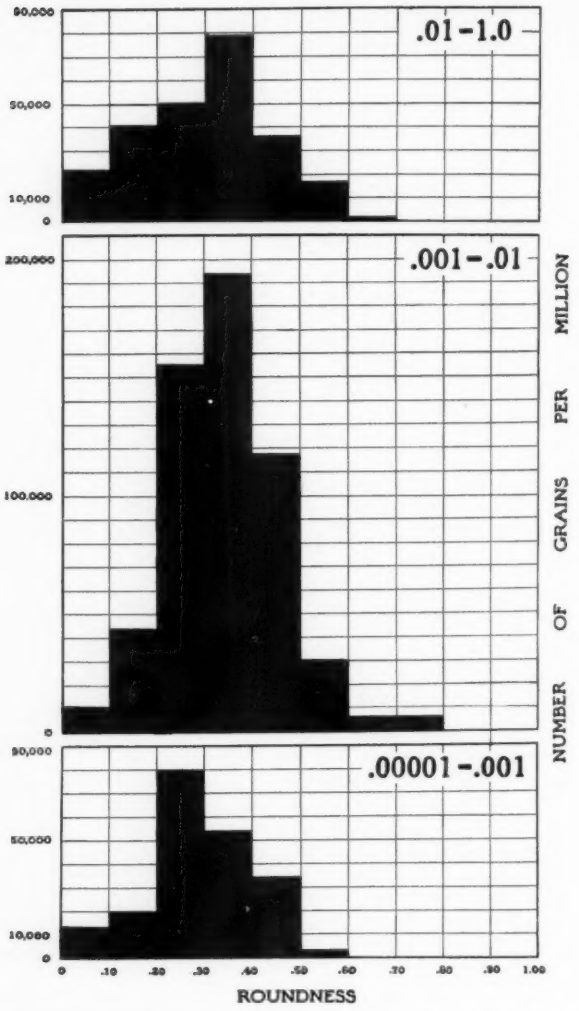


FIG. 6.—Distribution of one million grains classified according to volume and P-value (arithmetic scale).

no further. The percentage of porosity of the compacted sand was determined by the formula:[17]

$$P=\frac{100(C-V)}{C},$$

where, C is the volume of sand and voids, V the actual volume of all sand grains, and P is the percentage of porosity with maximum compaction.

The relative "angularity" of the sand was determined by dividing 25.95, the theoretical minimum porosity for spheres, by the porosity of the compacted sample. Lamar concludes that the nearer the figure is to 1.00, the "rounder" the sand. "Round" must here be considered as synonymous with "spherical."

Lamar's conclusion appears to be justified, provided that: (1) the grains are of approximately the same size so that the pore-space is not filled with smaller particles; (2) the particles do not vary greatly in shape, and (3) the grains are somewhat irregular in shape and do not possess geometric forms which permit complete compaction (cubes). These provisions are reasonably well fulfilled in respect to grade sizes obtained by screening St. Peter sand. Yet, on account of the varying irregular shape of the particles, it is difficult to obtain a clear mathematical analysis of the problem. We may, however, adopt Mitscherlich's viewpoint, namely: (1) the form of the pore-space is governed by the shape of the particles and the mode of packing; and (2) the pore-space becomes more branched with the increasing sum of the particle surfaces.[18]

Since the sum of the surface areas of particles of a given sieve size increases with decreasing degree of true sphericity, it is conceivable, on the basis of the reasoning presented above, that porosity values are to a large extent influenced by the sphericity values of the

[17] Lamar's formula is given as, $P=\frac{C-V\times 100}{C}$; it is obviously a misprint or *lapsus calami*.

[18] Eilh. A. Mitscherlich, *Bodenkunde für Land- und Forstwirte* (1905). P. 84, "Die Gestalt des Hohlraumvolumen des Bodens wird bedingt durch die Gestalt der einzelnen Teilchen und durch die Art der Aneinanderlagerung." P. 86, ". . . . das Hohlraumvolumen um so verzweigten ist, je grösser die Summe der Oberfläche der festen Bodenteilchen ist."

grains. The arithmetic mean of the ϕ-values, obtained for each sieve in the present study, is given in Table VI. Thus, the value 0.829 for the 0.250 mm. sieve is the arithmetic mean of the ϕ-values given in Table III. The corresponding porosity value has been obtained by dividing 25.95, the figure used by Lamar for computing the "angularity" value, by the average ϕ-value. Lamar's porosity and "angularity" values, the latter actually expressing the average grain shape, may serve for comparison. The average values for porosity

TABLE VI

St. Peter Sandstone (Wadell)			Average of 9 Samples of St. Peter Sandstone (Lamar)			Crushed "Cypress Sand" (Lamar)	
On Sieve (Mm.)	Arithmetic Mean of ϕ-Values	Percentage of Porosity	On Sieve (Mm.)	Relative "Angularity"	Percentage of Porosity	Relative "Angularity"	Percentage of Porosity
0.500	0.852	30.4	0.417	0.809	32.1	0.574	45.2
0.250	0.829	31.3	0.295	0.773	33.6	0.649	40.0
0.125	0.824	31.4	0.208	0.735	35.3	0.659	39.4
0.061	0.804	32.2	0.147	0.712	36.2	0.641	40.5

and "angularity" of nine samples of St. Peter sand are given in Table VI, which also includes the values obtained by Lamar for "Cypress sand," to show the difference in result obtained for artificially crushed and very "angular" sand.

Comparing the figures obtained by Lamar and the present writer it should be noted that: (1) the screen openings applied by Lamar are somewhat different from those used in the present study; (2) Lamar's samples were collected in other localities, but, with two exceptions, situated within a few miles' distance from the locality of the sample used in this study; and (3) Table VI gives average values for nine samples. Lamar's maximum and minimum values (not given in Table VI) for "angularity" amount to 0.852 and 0.692 respectively, thus comparing favorably with the maximum and minimum average ϕ-values of Table VI. The relatively higher values, obtained both by Lamar and the present writer for St.

Peter sand, present a notable contrast to the lower values of the artificially crushed "Cypress sand."

Table VII gives the arithmetic mean of the roundness values (P) obtained for each sieve size. For instance, the average roundness value for grains of the 0.250-mm. sieve amounts to 0.350, which is the arithmetic mean of the roundness values (P) listed in Table III. Table VII shows that the average roundness value increases toward

TABLE VII

On Sieve (mm.)	Average P
0.500	0.423
0.250	0.350
0.125	0.332
0.061	0.285
Pan	0.288

the higher grade-sizes, thus in conformity with Sorby's[19] general observations in respect to worn sands.

GENERAL REMARKS

A presentation of new methods is the main purpose of this paper. The diagrams will be interpreted in a forthcoming paper. Only a few points bearing on the accuracy and possibilities of the proposed methods will be taken up here.

Before attempting any interpretation of the diagrams, we must consider how reliably the obtained values express the particle properties. The measurement of the nominal sectional diameter has already been sufficiently discussed and is believed to be superior to any other method proposed for measuring the size of a small quartz particle directly.

The ϕ-values are, perhaps, the most unreliable data presented in this paper. The paucity of available experimental data made it necessary to adopt the five prototypes as a base for reasoning, which, although admittedly weak in many points, nevertheless proved to hold rather well in respect to 62 experimental determinations of

[19] *Op. cit.*

settling velocities of larger fragments (pebbles) of irregular shapes.[20] It was shown that the settling velocities of fragments of the same volume and specific gravity in general decreased with decreasing degree of true sphericity (ψ) and that the same rule can be applied to the ϕ-values with some modification. It was also found that the practical formulas obtained on the basis of the five prototypes were reasonably well in accord with the coefficient of resistance as a function of Reynolds number for the various fragments. It should be especially noted, in defense of any eventual inadequacies in the ϕ-values, that our present interest does not lie so much in the structural details of the resulting diagrams, but rather in their general character, showing the tendency toward high or low sphericity for the majority of particles in each volume-class. For instance, Figure 5 shows a marked increase of the ϕ-values among the particles of the higher volume-classes, 0.01–1.0. The sphericity class 0.80–0.85 is the modal group in the volume-class 0.001–0.01, while the modal sphericity group rises to the ϕ-class 0.85–0.90 in the next higher volume-class, 0.01-0.1. The particles in the highest volume-class, 0.1–1.0, are too few for comparison, but one notes even here a marked general increase in the sphericity, the lowest ϕ-value being represented by 3 particles in the ϕ-class 0.75–0.80, whereas in the volume-class below there are more than 15,000 particles in the ϕ-class 0.65–0.70.

The question arises whether the general increase in sphericity toward the higher volume-classes is in accord with facts or due to inadequacies of the methods. It has been previously pointed out that particles of high ϕ-values may have either a high degree of true sphericity or the shape of a more or less circular disc of very low ψ-value. It was possible, however, to measure the thickness of the particles by well-known microscopic methods, which showed all particles of high ϕ-values to be more or less equidimensional, a fact which suggests that the ϕ-value expresses reasonably well the actual ψ-value.

Exact roundness values can be procured provided that the outlines of the grains are carefully reproduced with steady hand. The

[20] Wadell, "Shape Determinations of Large Sedimental Rock-Fragments," *loc. cit.*

variation in result, due to slight variations in position of a particle in reproduction, does not exceed one class-interval. However, for uniform results, all particles should be reproduced as nearly as possible in the plane of the longest and intermediate diameters.

Both the sphericity and the roundness of a sand grain are visualized by the so-called "image value," which has been described and illustrated in a previous paper.[21] The "image value" has, however, no sedimentological significance.

In an attempt to interpret the structure of the diagrams it is important to bear in mind that the frequencies are built on frequency values of the investigated particles. If the frequency values, as derived from the number of particles on each sieve, vary greatly, the resulting diagrams of volume classes, carrying but a few investigated particles, may present an irregular structure of no real significance. Since the volume-classes are entirely artificial, we cannot expect to find any extreme difference in the sphericity and roundness of particles in two adjacent volume-classes, although in actuality great difference may exist, which could be visualized in a diagram if we could find the proper volume-class limits resulting in maximum differentiation. If, therefore, any excessively irregular structure is encountered in a diagram for a given volume-class, without at least indications of corresponding irregularities in adjacent volume-classes, the irregular structure must in most cases be attributed to the frequency values and an insufficient number of investigated particles. For example, the high frequency in ϕ-class 0.70–0.75 of volume-class 0.0001–0.001 (Fig. 5) is most likely an irregularity of the type described, because there is no indication of pronounced frequency in the same ϕ-classes of the volume-classes next above and below.

If the numbers of investigated particles in one or several volume-classes are too few, these classes are either united or combined with an adjacent volume-class. The diagrammatic structure thereby becomes more pronounced and the tendency of the particle properties is better visualized. Some of the volume-classes in Figure 6 were united and the same could well have been done in respect to corre-

[21] Wadell, "Volume, Shape and Roundness of Rock Particles," *loc. cit.*

sponding volume-classes in Figure 5. It was, however, desirable to retain Figure 5 in its original form in order to illustrate the discussion above.

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THE COMPOSITIONS OF SOME AFRICAN GRANITOID ROCKS

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ABSTRACT

Analyses and brief petrographic notes are here given for twenty-one large intrusives from the African shield. These, with about as many earlier tests, indicate that the core of the continent is not abnormal in composition, as might be supposed from the numerous analyses made on alkalic and basic rocks near the coasts.

INTRODUCTION

This paper is essentially a record of analyses and brief petrographic notes. The Fifteenth International Geological Congress brought the writer in touch with some of the problems of African batholiths and some of the geologists who are working on them. Director Maufe of the Geological Survey of Southern Rhodesia reported that a series of analyses of granites were on file; but, aside from these, there seemed to be relatively little chemical evidence as to the nature of the larger granitic masses of the southern half of the continent. Interest has centered in the rocks of commercial possibilities in the Bushveld and in the odd alkalic rocks. There seemed to be no doubt that an average of existing analyses, such as that used by Clarke and Washington,[1] would include too few granite analyses to indicate the nature of the region. They reported that the 223 analyses of African rocks up to 1913 are without adequate representation of the interior and are almost certainly too alkalic and too low in silica.

Washington[2] reported only 15 or 20 analyses of granite from the southern part of Africa available in 1914. Iddings found few in 1913 to illustrate the region.[3] A bare half-dozen analyses of granite from

[1] F. W. Clarke and H. S. Washington, *U.S. Geol. Surv. Prof. Paper 127* (1924), pp. 62–64.

[2] *U.S. Geol. Surv. Prof. Paper 99.*

[3] J. P. Iddings, *Igneous Rocks*, Vol. II (1933), pp. 569–88.

South Africa were reported by Du Toit in 1926.[4] Only one analysis of "old granite" was available in 1926.[5]

This condition has no doubt been corrected by the addition of about as many more since 1914,[6] but interest in alkalic and basic rocks has not abated, and there are new analyses of those also. The writer therefore collected a few samples under the guidance of the congress leaders and has had the good fortune to interest Dr. D. L. Scholtz, of Pretoria, and Dr. D. M. Davidson, of Mufulira, in Northern Rhodesia, who have supplied several others. Under the circumstances no apology seems necessary for the lack of more extended field data and maps to accompany the results. Granites may, and in some parts certainly do, make up as high a proportion of the bedrock in the African shield as in the Canadian shield. The basement complex of Southern Rhodesia is 85 per cent granite.[7]

Analyses have been made by the chemists of the University of Minnesota Laboratory for Rock Analysis at such times as they were not kept busy by other petrographers; and some financial help from the research funds of the University of Minnesota Graduate School is gratefully acknowledged. Two analyses were added by Mr. J. L. Lindner as a student problem.

Most of the analyses here reported are of the granites called "older." They are intrusive only into the basement schist or Swaziland system. It is recognized, however, that granites of two ages are present in this relation.[8] The younger granites are small and per-

[4] A. L. du Toit, *Geology of South Africa* (1926), pp. 445–46.

[5] J. Willemse, "Petrography and Tectonics of the Pretoria-Johannesburg Granite," *Trans. Geol. Soc. So. Africa*, Vol. XXXVI (1933), p. 10.

[6] For example, a number of granite analyses have been issued by the members of the Geol. Surv. of So. Africa, as in *Mems. 16* and *28;* several by the Geol. Surv. of So. Rhodesia, as in *Bulls. 10, 12, 17, 22,* and *24;* some by the Gold Coast Geol. Surv., as in *Bull. 4;* see also papers in the *Trans. Geol. Soc. So. Africa*, Vol. XXXIV (1931), p. 86; *Quar. Jour. Geol. Soc.*, Vol. LXXXV (1929), p. 144; and Vol. LXXXVIII (1932), pp. 458 and 491; and A. L. Hall and G. A. F. Molengraff, *The Vredefort Mountain Land*, "Shaler Memorial Series" (1925); R. A. Daly, *Geol. Soc. Amer. Bull. 39* (1928), pp. 703–68.

[7] A. M. Macgregor, *Geol. Mag.*, Vol. LXIX (1932), pp. 18–29.

[8] T. W. Gevers, *Trans. Geol. Soc. So. Africa*, Vol. XXXII (1929), pp. 31–55; P. A. Wagner, *ibid.*, Vol. XXIV (1921), p. 73; G. C. A. Jackson, *Quar. Jour. Geol. Soc.*, Vol., LXXXVIII (1932), pp. 454–91.

haps mostly related to the igneous activity at the time of intrusion of the Bushveld complex—namely, pre-Devonian but not certainly pre-Cambrian. With this uncertainty of age of the later granites, the older may be scattered widely through the pre-Cambrian. Some of the "older" granites look fresh and unaltered. As in the other shield areas, the granites of a district have a different appearance if they are of two periods, even if not far separated. The latest granite of a district appears fresh even if early pre-Cambrian, and the older of two looks metamorphic even if late Paleozoic. In other words, it is noted that batholiths may develop in cycles; and in each cycle the old masses are gray gneiss, the younger, red granite.[9] Still it is significant that migmatitic gneisses are seen almost exclusively in pre-Cambrian shields as if exposed only by deep erosion;[10] hence, probably the gneisses are old, but some of the red granites may be of about the same age. As to the age of some masses, there is still uncertainty.[11]

The modes reported with the analyses are rough measurements because only a single section was available for most rocks; and several are coarse, several are banded, and several are altered hydrothermally. In such rocks measurements of the main constituents may differ from the correct values by several per cent, but the measurement is nevertheless better than no estimate at all. The numbers on the descriptions correspond to those on the tables of analyses and notes. The names given in the notes with analyses, following the measured modes, are based on Johannsen's classification; and these are followed by the name and numerical symbol of the C.I.P.W. system.

The samples are from districts scattered all the way from the border of the Congo south: six from Northern Rhodesia, five from Southern Rhodesia, five from the Transvaal, and five from the rest of the Union of South Africa. These should give at least a prelimi-

[9] G. C. A. Jackson, "Geol. of N'Changa District, N.R.," *Quar. Jour. Geol. Soc.*, Vol. LXXXVIII (1932), p. 494.

[10] A. M. Macgregor, *Geol. Mag.*, Vol. LXIX (1932), pp. 18–29.

[11] Shand and Du Toit take different points of view as to the Palabora rocks. *Trans. Geol. Soc. So. Africa*, Vol. XXXIV (1931), pp. 81–127.

nary notion as to the granites of the south half of the continent, except for some along the west side (Fig. 1).[12]

NORTHERN RHODESIA

The samples from Northern Rhodesia are the diamond drill cores taken in explorations for copper, because most outcrop samples are badly weathered. No fresher samples than these are likely to be available for a long time. The granites near the copper ores are mostly younger than the Roan series of copper-bearing sediments.[13] Two samples of older gneiss are included, however.

1. The granite from a drill hole at Chambishi at a depth of 1,010 feet is gray, and intrudes the Roan series. The quartzes have a slight bluish tone. Gneissic structure is hardly visible in the core, but the thin section shows both deformation and mineralization. Some of the few grains of fresh feldspar and some of the biotites are bent; and nearly half the rock consists of wholly sericitized feldspar. Carbonate makes up a small percentage, part introduced and replacing feldspar, but part interlocked with quartz, as if primary.

2. The granite from the first drill hole at Kalulushi was found to intrude the Roan sediments at a depth of 650 feet. It is pink but has pale greenish sericitic spots. There has been very little deformation, but a late attack on minerals is prominent. This seems to have left hardly any plagioclase, though there may have been some originally, besides the perthite still visible. The quartz is abundant and replaces the feldspars along the boundaries, but not in fractures, as might be expected from hot-water attack. It is probably a deuteric mineral, or, taken with the presence of abundant microcline, it may indicate a pegmatitic stage of magma evolution. The sericite and carbonate are clearly later and may have resulted from hot waters in fractures. There is little kaolinization. If the field relations had not been clear, the mineral and chemical characters might have left some doubt whether the rock was granite or arkose.

3. Gray granite gneiss was encountered in the first hole at Mwe-

[12] Those given by Chudoba for the Erongo are young granites. *Neues Jahrb. Bb. 66*, B, p. 126.

[13] Anton Gray, *Geology and Ore Deposits of the N'Kana Concession* (London, 1929); D. M. Davidson, "Geology and Ore Deposits of Chambishi," *Econ. Geol.*, Vol. XXVI (1931), pp. 131–37.

kera at 120 feet. In spite of its gneissic character, it is thought to be intrusive into the Roan series. Possibly the gneissic structure is considerably later than intrusion, for it has more the character of granulation than magma flowage. Many quartz areas are broken

FIG. 1.—Sketch map of the southern part of Africa, to indicate by spots the approximate location of granites and gneisses here tested.

down to a mosaic, and those not broken are crossed by very prominent strain shadows. The feldspar and biotite are also deformed and the plagioclase fractured and healed by veins of the same feldspar a little clearer than the dusty originals. Biotite is partly green but, where altered, more of a yellow. The metamorphism may be a result of regional folding, but perhaps more likely of later granite intrusion.

4. At N'Dola the drill hole at the "Boma" water hole was in gray

granite gneiss at a depth of 100 feet. This also is believed to intrude the country rock, and part of the gneissic character may be a schistosity inherited from that rock. The injected granite portions may be almost massive, but there has been much replacement and recrystallization of the foliated rock. As a mixed rock it is now largely igneous. The abundant epidote probably explains why the plagioclase is more sodic than might be expected from the analysis and norm calculation. The coarse quartz not only replaces a variety of earlier minerals, leaving only a ghost outline of residual inclusions, but it has been shattered, sheared, and healed, leaving a rift structure of fluid inclusions along planes..

5. At Mutondo the first drill hole was in somewhat altered granite at a depth of 400 feet. This differs from No. 4 in having probably been massive in the first place and not especially gneissic in the drill core, but clearly granulated, and veined in the thin section. The abundant quartz, feldspars, and mica are broken and bent, and have very wavy extinction. The mica is a very pale brown phlogopite, a little more colored in the centers than at the edges of grains. There is some darker secondary biotite; and veins and shear streaks show some quartz in a mosaic pattern. Hydrothermal action has made the rock more hydrous than the rest of the group. The plagioclase, though sodic, is not very abundant.[14]

6. North of Broken Hill the "old granite" intrudes the basement (Swaziland) schists. Most of the outcrops are gneissic from granulation and recrystallization and some feldspar phenocrysts are augen, but it is not very certain whether the structure was developed before or after the first cooling of the intrusive. There is a parallelism of biotites that seems primary in addition to a bending of mica and granulation of the edges of some quartz and feldspar. Myrmekite indicates a considerable amount of late reaction in the cooling magma. Weathering to kaolinite is more conspicuous than in drill cores. Locally at Lunsemfwa the gneiss is cut by a chalcopyrite aplite that is younger (or a late phase), but this has not been analyzed.

[14] Johannsen's classification places it in the "sodaclase granites" simply to distinguish it from normal granites which have oligoclase; but it has much more potash feldspar than sodaclase.

In partial summary, the Northern Rhodesian granites and gneisses show no very great variety except that in certain places potash may

TABLE I

ANALYSES OF GRANITE FROM NORTHERN RHODESIA

	1	2	3	4	5	6
SiO_2	68.64	77.22	70.95	75.20	71.82	70.54
Al_2O_3	13.95	11.49	15.07	10.10	14.41	14.75
Fe_2O_3	1.14	1.03	1.13	1.55	1.26	0.35
FeO	1.25	0.22	1.29	1.69	0.35	2.38
MgO	2.29	0.38	1.32	2.81	1.25	0.72
CaO	2.25	0.28	0.83	2.08	0.41	2.04
Na_2O	2.13	0.30	4.23	2.02	0.50	2.37
K_2O	4.04	7.26	3.03	2.13	5.96	4.77
H_2O+	1.68	0.81	1.21	0.91	2.44	1.10
H_2O-	0.09	0.06	0.09	0.20	1.32	0.06
CO_2	1.77	0.29	trace	0.07	0.22	0.04
TiO_2	0.30	0.13	0.42	0.33	0.20	0.37
ZrO_2	n.d.	n.d.	n.d.	none	n.d.	0.01
P_2O_5	0.11	0.24	0.11	0.34	0.12	0.19
S	trace	0.01	trace	0.02	0.01	0.01
MnO	0.06	trace	0.03	0.04	trace	0.02
BaO	0.03	0.13	0.05	0.08	0.07	0.08
Cl	n.d.	n.d.	n.d.	0.05	n.d.	n.d.
Total	99.73	99.85	99.76	99.62	100.34	99.80

1. Younger granite from Chambishi. Drill hole No. 26, depth 1,010 feet. Quartz 30%, biotite 3%, carbonate 4%, feldspars 63%, mostly sericitized. A leucogranite. Toscanose, I·4·2·3. R. B. Ellestad, analyst.

2. Younger granite from Kalulushi. Drill hole No. 1, depth 650 feet. Quartz 40%, microcline 40%, partly sericitized feldspar (mostly perthite) 15%, accessory muscovite and secondary hematite and carbonate. A kalialaskite. Bisbose, I·3·1·1. T. Kameda, analyst.

3. Younger granite from Mwekera. Drill hole No. 1, depth 120 feet. Quartz 33%, albite 40%, potash feldspars 16%, biotite 6%, muscovite 3%, besides apatite, sericite, epidote, and secondary iron oxides. A sodaclase granodiorite. Kallerudose, I·4·1·4. R. B. Ellestad, analyst.

4. Younger granite gneiss from N'Dola, "Boma" water hole, depth 100 feet. Quartz 50%, orthoclase and silicic plagioclase each 15%, epidote 15%, biotite 5%, besides zircon, sericite, and chlorite. A quartz granite. Tehamose, I·3·2·3. T. Kameda, analyst.

5. "Old granite" from Mutondo. Drill hole No. 1, depth 400 feet. Quartz 40%, microcline 35%, albite 10%, micas 5%, magnetite 3%, the remainder mostly sericite but with hematite, and some veinlets of carbonate and quartz. A sodaclase granite. Bisbose, I·3·1·1. T. Kameda, analyst.

6. "Old granite" gneiss outcropping north of Broken Hill. Quartz 30%, oligoclase 25%, microcline 30%, orthoclase 15%, biotite 5%, muscovite 2%, besides zircon, sericite, chlorite, and carbonate. Toscanose, I·4·2·3. Frank F. Grout, analyst.

increase almost to the exclusion of soda. This condition may be found in granites that are considered "old," as well as in younger masses, and probably represents a pegmatitic or hydrothermal stage of the intrusive. Several have so much alumina that corundum is calculated in the norm, but this is not found in the rocks; it is probably a consequence of some muscovite in the mode.

SOUTHERN RHODESIA

All the samples of granite from Southern Rhodesia tested in this study were sent by Dr. D. L. Scholtz, and some may be from the same masses studied by the geologists of the Rhodesian Survey. Large chunks from fresh outcrops have been crushed to yield fair samples. All are believed to be "older" granites, but none of those obtained shows any prominent signs of great age or history of attack. They intrude the basement complex schists but are not everywhere in contact with younger formations.

7. About 30 miles north of Fort Victoria, an outcrop west of Gutu is a light brownish gray, medium to fine grained granite. No signs of deformation were noted except such wavy extinction as is almost universal in granites, and rarely a broken grain of feldspar. The quartz carries some very minute rutile needles but rarely any liquid and gas inclusions. Hydrothermal attack and weathering increase the list of minerals, but all are in very minute amounts. It is no more altered than the younger granites.

8. The quarry rock at Dett is a fresh looking, gray, medium grained granite. Some of the feldspars show wavy extinction, but no great deformation is indicated. Besides the separate grains of orthoclase, microcline, and plagioclase there are grains that seem to be cryptoperthite. Myrmekite encroaches on the potash feldspars. Hydrothermal effects are noted but not at all prominent, and weathering has produced more kaolin than in some of the rocks not quarried. The color and uniformity of the rock are the desired qualities in the quarry rock.

9. At Mudzi River, M'toko district, a medium grained granite has a gray to faint pinkish color. It has a few large phenocrysts; and the thin section reveals a few bent and granulated grains, but not enough to make it gneissic. Some of the quartz is in the myrmekite,

but more is in normal grains or in patches of a mosaic pattern. Euhedral plagioclase in small grains occurs enclosed in coarser

TABLE II

ANALYSES OF GRANITE FROM SOUTHERN RHODESIA

	7	8	9	10	11
SiO_2	73.70	71.42	72.19	70.21	72.95
Al_2O_3	14.48	14.23	14.28	14.80	13.52
Fe_2O_3	0.42	0.59	0.55	0.90	0.61
FeO	0.80	1.85	1.30	1.81	0.83
MgO	0.37	0.70	0.48	0.81	0.41
CaO	1.09	2.30	1.14	1.96	1.09
Na_2O	3.67	3.21	3.25	4.17	3.33
K_2O	5.07	3.51	5.67	3.76	5.80
H_2O+	0.53	0.72	0.42	0.37	0.43
H_2O-	0.01	0.06	0.05	0.04	0.02
CO_2	0.05	0.06	0.17	0.12	0.25
TiO_2	0.14	0.35	0.25	0.40	0.19
ZrO_2	0.01	0.01	trace	0.02	0.04
P_2O_5	0.17	0.36	0.35	0.35	0.09
S	0.01	0.02	0.01	0.01	0.01
MnO	0.03	0.04	0.03	0.03	0.03
BaO	0.07	0.05	0.05	0.07	0.05
Total	100.62	99.48	100.19	99.83	99.65

7. "Old granite" west of Gutu. Quartz 23%, oligoclase 35%, microcline 28%, orthoclase 8%, biotite 3%, with accessory apatite, magnetite, and rutile, and secondary sericite, epidote, chlorite, and brown iron oxides. A leucogranite or normal granite. Liparose, I·4·1·3. J. L. Lindner, analyst.

8. "Old granite" in quarry at Dett. Quartz 27%, potash feldspars 37%, oligoclase 30%, biotite 5%, accessory magnetite, apatite, and zircon, secondary chlorite, sericite, kaolinite, leucoxene, and brown iron oxides. Toscanose, I·4·2·3. Frank F. Grout, analyst.

9. "Old granite" along Mudzi River. Quartz 28%, oligoclase 33%, orthoclase and perthite 33%, biotite 5%, accessory muscovite, apatite, and zircon, secondary sericite and calcite. Liparose, I·4·1·3. T. Kameda, analyst.

10. "Old granite" in Matopo Hills, south of Bulawayo. Quartz 25%, oligoclase 35%, microcline 28%, orthoclase 5%, biotite 3%, with minor muscovite, magnetite, apatite, zircon, sericite, and chlorite. A leucogranite. Toscanose, I·4·2·3. T. Kameda, analyst.

11. "Old granite" 25 miles south of Salisbury. Quartz 25%, albite-oligoclase 28%, microcline 23%, orthoclase 20%, biotite 3%, and small amounts of magnetite, apatite, zircon, fluorite, titanite, sericite, chlorite, iron oxides, carbonate, and kaolinite. An alaskite or leucogranite. Liparose, I·4·1·3. J. L. Lindner, analyst.

orthoclase. Biotite shows dark halos around zircons; and muscovite is late (possibly dueteric), replacing feldspar.

10. The prominent granite of the Matopo Hills is well known around Bulawayo. It is a brownish gray, medium grained, massive granite. Deuteric reaction produced some myrmekite, and hydrothermal attack made sericite of some of the oligoclase without affecting the potash feldspars.

11. At Hunyani River 25 miles south of Salisbury there is a coarse porphyritic, brownish gray granite. Primary mineral intergrowths include myrmekite and perthite. There has been some attack, by hot water and by weathering, forming many minerals, but none in important amounts. Fluorite is an exceptional one but is recorded also in Northern Rhodesia.

The samples available show very slight differences among the "older" granites of Southern Rhodesia. Quartz and the potassic and sodic feldspars have the proportions characteristic of normal granites. All have nearly 5 per cent of dark minerals, so that they are close to the line that Johannsen draws between granite and leucogranite.

TRANSVAAL

Samples of many igneous rocks of the Transvaal have been analyzed and reported on by the geologists working in and near the Bushveld complex and Johannesburg. Five samples have been tested for the present set of analyses; and although some may almost duplicate earlier work, there are some features of interest in the check results.

12. An occurrence about 25 miles south of Messina, although light gray and granitoid, proves to have no quartz, but an abundance of labradorite. It is a gabbro that was no doubt collected because of its resemblance to the granites of the series.

13. "Old granite" at Pietersburg Town is light gray, medium grained, and practically massive. The abundant plagioclase grew early, and some euhedral grains are enclosed in coarser microcline; others simply lie in a matrix of the other minerals. The quartz in large grains has a prominent wavy extinction as if strained, and there are interlocking sutured quartzes that may be recrystallized. The potash feldspar is very fresh even when the adjacent or included plagioclase is very sericitic. The classification as granite or granodi-

orite depends on the composition selected for separating silicic and medium plagioclase. This rock is near the dividing-line.

TABLE III

ANALYSES OF CERTAIN ROCKS OF THE TRANSVAAL*

	12	13	14	15	16
SiO_2	48.19	72.06	72.42	79.58	73.92
Al_2O_3	26.54	14.78	15.19	8.91	14.07
Fe_2O_3	0.99	0.52	0.78	0.52	0.52
FeO	3.22	1.46	0.88	2.26	0.89
MgO	2.59	0.72	0.63	0.17	0.38
CaO	13.99	1.40	1.67	0.69	1.22
Na_2O	2.50	5.00	5.24	2.48	3.83
K_2O	0.35	2.42	1.62	3.89	4.35
H_2O+	0.65	0.71	0.84	0.33	0.44
H_2O-	0.06	0.02	0.04	0.08	0.01
CO_2	0.05	0.43	0.13	0.04	n.d.
TiO_2	0.42	0.28	0.23	0.23	0.21
ZrO_2	none	none	none	0.02	none
P_2O_5	0.20	0.10	0.09	0.29	0.09
S	0.01	0.01	0.02	0.01	0.01
Cr_2O_3	0.18	n.d.	n.d.	n.d.	n.d.
MnO	0.06	0.04	0.02	0.05	0.04
BaO	0.01	0.04	0.04	0.14	0.02
Total	100.01	99.99	99.84	99.69	100.00

*All analyses by T. Kameda.

12. Gabbro about 25 miles south of Messina. Labradorite 78%, hornblende 21%, biotite fringes on the hornblende. Hessose, II·5·4·5.

13 and 14. "Older granite" and gneiss were collected at outcrops in Pietersburg and 2 miles south, probably from the same mass. Quartz 30%, albite 45%, orthoclase and microcline 18%, biotite 5%, accessory muscovite, apatite, secondary epidote, chlorite, sericite, and others. A granodiorite and equivalent gneiss. Lassenose, I·4·2·4.

15. Young granite from a drill hole about 5 miles west of Magnet Heights, Bushveld. Quartz 45%, perthite 45%, hornblende 5%, albite 4%, accessory biotite, zircon, apatite, and magnetite, traces of secondary sericite and kaolinite. A sodaclase granite. Alaskose, I·3·1·3.

16. "Old granite" at Halfway House, Pretoria-Johannesburg. Quartz 32%, oligoclase 40%, orthoclase and microcline 25%, biotite 3%, accessory iron oxide and secondary traces of sericite, epidote, chlorite, leucoxene, and kaolinite. A leucogranodiorite. Toscanose, I·4·2·3.

14. "Old granite" gneiss 2 miles south of Pietersburg is much like the granite just noted but has been granulated and recrystallized so that it looks decidedly older. Micas are bent, and quartz and

feldspars granulated in large part. Quartz forms a mosaic in patches or streaks, and the feldspar is slightly stained to a pinkish brown.

15. Hall has reported an analysis of granite from this drill core west of Magnet Heights which shows some odd features,[15] especially an alumina content rather lower than average granites. The average pre-Cambrian granite has over 14 per cent alumina, and several South African rocks about 11 per cent; this drill core has less than 9 per cent. The core shows a pink, massive, medium grained hornblende granite in which one would hardly suspect that there was nearly 50 per cent quartz. The hornblende in thin section is a brownish green with lighter spots, suggesting that it may have formed by a deuteric change from pyroxene. A little kaolinite dusts the orthoclase but not the albite, even in the perthitic intergrowth.

16. The "old granite" of the Pretoria-Johannesburg batholith is a massive, medium grained, gray granite with little petrographic sign of age. The plagioclases are zoned with average composition about 13 per cent anorthite, the central calcic zones being considerably dusted with sericite while the outer remains clear.

This Transvaal group is the most miscellaneous of any of the groups here reported, including a gabbro, a granite with exceptionally low alumina, and two rocks from Pietersburg probably of the same mass but of different structure.

SOUTHERN PARTS OF UNION OF SOUTH AFRICA

A group of five samples are from scattered parts of the Union, ranging from the border of Transvaal to Cape Town and Natal. All but the first were collected by Dr. D. L. Scholtz, and consist of large chunks from fresh outcrops. All are believed to be "older" granites except the Nama granite of the Cape; but this younger granite is gneissic, and one of the "old granites" from Natal is almost massive.

17. In Orange Free State, at the Vredefort dome (a remarkable structural feature),[16] the main central granitic intrusive seems to be older than the dome and is said to have been upthrust and probably

[15] A. L. Hall, "The Bushveld Igneous Complex," *Geol. Surv. of So. Africa Mem. 28* (1932), pp. 375–82; B. V. Lombaard, *Trans. Geol. Soc. So. Africa*, Vol. XXXVII (1934), p. 9.

[16] A. L. Hall and G. A. F. Molengraaff, *op. cit.*

violently disturbed by the shock of doming. Nevertheless, the granite gneiss at a quarry on the south side of the Vaal River near Parys, although said to be "old," is pink, and seems to owe its gneissic structure to injection of older schists or gneiss. The signs of deformation are not the common widespread granulation, but a locally concentrated granulation forming a flinty crush rock or pseudo-tachylite. The pink rock with about an average amount of biotitic schlieren was selected for analysis to compare with other "old granites." The thin section shows more signs of metamorphism than were expected. Feldspars and biotite are bent, and the biotite is dusty and altered to chlorite and magnetite. The feldspars are considerably kaolinized. The quartz has several noteworthy characters. Besides some myrmekite intergrowth, there is an interlocking of quartz grains with each other in a mosaic or skeletal pattern. There is, further, an abundance of liquid and gas inclusions in quartz; and the gas bubbles are large, as if formed at high temperatures. Although the inclusions follow planes, as if healing fractures, their characters and abundance rather suggest that the features of the quartz may all have developed at a pegmatitic or deuteric stage of magma history.

18. At Hlatikulu, southeast of Mbabne, Swaziland, an old, gray banded gneiss has intruded the old schists. Some of the structure is probably a result of lit-par-lit injection into schists, or to schlieren of partly melted or differentiated material, for there is relatively little granulation. In the specimen the lighter colored bands are chalky with kaolinized albite, and the grayer bands are more vitreous microcline or quartz. Clearly the microcline has been less attacked than the plagioclase.

19. The young "Nama granite" of the Cape Province outcrops at George, intruding the Malmsbury series. It is supposed to be pre-Cambrian and has a gneissic structure, evidently from metamorphism. It is a gray, muscovite-biotite rock, with feldspars bent and all the original minerals showing wavy extinction. Orthoclase grains develop a microcline twinning where probably strained near borders and cracks. Quartz is granulated into streaks and recrystallized into a mosaic pattern. Zircon inclusions make conspicuous halos in biotite and chlorite.

20. The "old granite" west of Hillcrest at Camperdown, Natal, is only slightly gneissic and may have been massive as intruded. The

TABLE IV

ANALYSES OF GRANITES FROM THE SOUTHERN PART OF THE UNION OF SOUTH AFRICA

	17	18	19	20	21
SiO_2	73.67	77.05	73.66	70.01	71.99
Al_2O_3	14.19	10.68	13.80	14.20	14.47
Fe_2O_3	0.41	1.10	0.34	0.42	0.15
FeO	1.10	1.71	1.42	3.24	1.31
MgO	0.42	0.34	0.46	0.55	0.34
CaO	1.43	0.93	0.94	2.06	1.25
Na_2O	4.26	2.52	2.62	3.14	3.37
K_2O	3.42	4.30	5.13	4.45	5.22
H_2O+	0.38	0.39	0.73	0.63	0.63
H_2O-	0.02	0.03	0.04	0.02	0.02
CO_2	0.16	0.22	0.07	0.15	0.53
TiO_2	0.19	0.28	0.22	0.48	0.30
ZrO_2	n.d.	0.02	0.02	none	n.d.
P_2O_5	0.06	0.29	0.22	0.20	0.10
S	0.02	0.02	trace	0.02	n.d.
MnO	0.02	0.03	0.04	0.06	0.02
BaO	0.05	0.05	0.01	0.11	n.d.
Total	99.80	99.96	99.72	99.74	99.70

17. Injection granite gneiss at Quarry near Vaal River. Quartz 30%, orthoclase 40%, oligoclase 25%, biotite 5%, with small traces of magnetite, chlorite, carbonate, and kaolinite. Toscanose, I·4·2·3. R. B. Ellestad, analyst.

18. "Old granite" gneiss from Hlatikulu, Swaziland. Quartz 43%, albite 20%, microcline 25%, orthoclase 5%, biotite 3%, magnetite 3%, traces of titanite, chlorite, carbonate, and kaolinite. A sodaclase granite. Alaskose, I·3·1·3. T. Kameda, analyst.

19. Young (?) granite gneiss from George, Cape Province. Quartz 40%, albite 25%, orthoclase, microcline, and perthite 30%, biotite 3%, muscovite 2%, accessory apatite and zircon, secondary sericite, chlorite, epidote, and carbonate. A leucogranite. Alaskose, I·3·1·3. Frank F. Grout, analyst.

20. "Old granite" west of Hillcrest, Camperdown, Natal. Quartz 28%, microcline and a little orthoclase 25%, perthite 20%, oligoclase 20%, biotite 7%, accessory allanite, apatite, zircon, and titanite, secondary sericite, chlorite, magnetite, and kaolinite. Toscanose, I·4·2·3. R. B. Ellestad, analyst.

21. "Old granite" of Port Shepstone, Natal. Quartz 30%, albite 32%, microcline 30%, orthoclase 3%, biotite 5%, accessory apatite, zircon, magnetite, titanite, and rutile, secondary sericite, chlorite, leucoxene, carbonate, iron oxides, and kaolinite. A leucogranite. Toscanose, I·4·2·3. A. Willman, analyst.

specimen is pinkish gray and so coarse as to be almost pegmatitic. Quartz is intergrown with feldspar in myrmekite, and with biotite

in a similar pattern. The large feldspars show gridiron twinning in part or all of the grains. The index of these grains is greater than 1.529, suggesting some soda in the potash feldspar; but some of the grains with gridiron twins have perthitic streaks, as if the soda feldspar had separated. Certain oligoclase grains are independent of this intergrowth in the coarse pink feldspar.

21. At Umzumbi River, Port Shepstone, Natal, the "old granite" is medium grained, light gray, and has only a slight gneissoid or flow structure, which seems primary rather than metamorphic. Like the gneiss near Mbabne, this rock has very fresh microcline but considerably altered albite. Besides sericite and carbonate, there is more kaolinite than in most of the samples. The quartz has rutile inclusions, and some tiny veinlets of carbonate cross all the original minerals.

GENERAL COMMENT

The granites and gneisses of the central parts of South Africa have about the chemical nature of granites and gneisses expected in shield areas. The basic and alkalic rocks common at the edges of central granite areas should not mislead one into thinking that Africa is fairly represented by the analyses of rocks near the coast. As Washington has noted,[17] Central Africa is probably largely granite.

Eight of the 21 new analyses are classed in the C.I.P.W. system as Toscanose, I·4·2·3 (persalic, quardofelic, domalkalic, and sodipotassic); and as many more differ in only one number in the numerical expression. In Johannsen's classification most of the rocks approach closely to granite. Five are (226) granites, and five are (216) leucogranites. Five others differ from granite in only one figure in the numerical expression.

As exceptional rocks may be noted two from the mineralized area in Northern Rhodesia that are high in potash; a few scattered samples show notably low alumina; and one granitoid rock as light colored as a granite proved to be gabbro.

Except for the gabbro and the hornblende granite of the Bush-

[17] H. S. Washington, "Granites of Central Spain," *Jour. Wash. Acad. Sci.*, Vol. XVI (1926), p. 412.

veld, all the analyzed samples were biotite rocks, and several have associated muscovite. Eleven are gneissic or gneissoid, and ten are almost entirely massive in hand specimen; but the gneissic condition cannot be correlated with any abundant chemical constituent. The gneisses have more combined water in the average, confirming the idea that the gneissic condition is a result of metamorphism.

Six of the analyses are from young granites and the rest are old, but this also cannot yet be correlated with any petrographic or chemical feature. Possibly the exceptionally high silica and low alumina are more common in younger granites, but it appears also in the "old granite" (No. 18) of Swaziland. The ratio of potash to soda is 1.8 in the average young granites and 1.3 in the older; but each ranges widely (from 0.7 to 12.0), so that no conclusions can be drawn from an analysis of one sample.[18]

[18] P. Eskola, "Petrology of the Orijarvi Region," *Com. Geol. Finlande, Bull.* 40 (1914), p. 63, notes more potash in later granites.

SOME MINOR FEATURES OF VALLEY GLACIERS AND VALLEY GLACIATION

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ABSTRACT

Most glacial studies have been chiefly concerned with motion, advance and recession, transportation by the ice, and the carving of land forms. The smaller features, discussed in this paper, have generally not been described. Many of these lesser features, located on and near the terminal parts of valley glaciers, are here named and described for the first time.

INTRODUCTION

It is the purpose of this paper to bring to the attention of those engaged in the study of both the existing glaciers and the Pleistocene glaciation some of the minor features developed in and around the ice of existing valley glaciers. The writer believes that a careful study of these features would help in the interpretation of the glacial phenomena of the Pleistocene and the present time.

A review of glacial literature shows that scant attention has been given to these minor features. Very little critical study has been given them since the classic investigations of Agassiz, Tyndall, and others in Europe, and those of T. C. Chamberlin, Reid, Russell, Gilbert, Hobbs, and others in America. The two most comprehensive treatises on the Alaskan glaciers[1] emphasize the position of the ice fronts, and their fluctuations in historic times, rather than the more minute features which are discussed in this paper.

What follows deals with observations made during a field season of four months in Alaska in the summer of 1931. Some fifteen glaciers were visited[2] under a grant from the National Research Council and Washington University, St. Louis. While the main purpose of this study was a consideration of rock-grooving by glaciers and by river ice in subarctic streams, an exceptional opportunity was also afforded for a study of the more minute glacial features.

[1] G. K. Gilbert, "Glaciers and Glaciation," *Alaska*, Vol. III (1904); R. S. Tarr and Lawrence Martin, *Alaskan Glacier Studies* (1914).

[2] Allen, Bartlett, Bear Lake, Camicia, Childs, Deadman, Grinnell, Herbert, Mendenhall, Miles, Norris, Spencer, Taku, Trail, and Valdez glaciers.

The writer wishes especially to thank Dr. C. K. Wentworth, of the Board of Water Supply, Honolulu, Hawaii, whom the writer accompanied in Alaska, for many valuable suggestions made both in the field and in the laboratory; also Dr. C. H. Behre, of Northwestern University, for many helpful suggestions. To many people in Alaska and the Yukon Territory, Canada, whose names limited space prevents listing, the writer is greatly indebted for numerous courtesies.

FEATURES OF THE ICE

Melting furrows between the ice granules.—On all of the Alaskan glaciers visited, it was noted that the surface of the small capillary

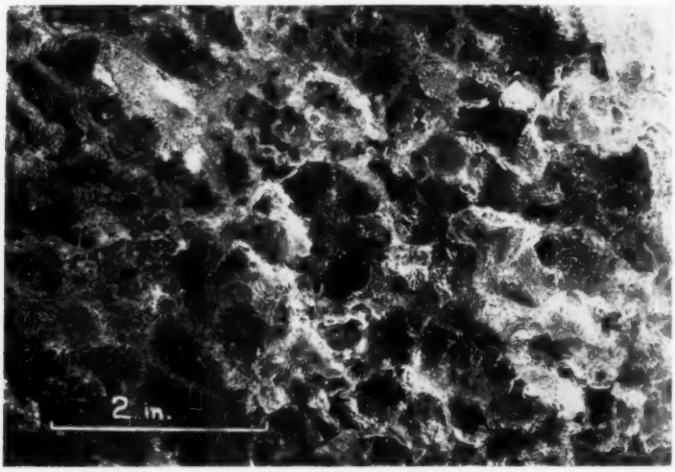

FIG. 1.—Glacial ice, showing granularity and "wrinkled" surfaces between the granules. Mendenhall Glacier.

openings between the ice granules, which serve as passages for the melting water, were roughened by small furrows, which resembled minute ripple-marks (Fig. 1). These roughened surfaces are the product of the uneven melting of the ice by the water passing between the granules. A moving sheet of water tends to become concentrated into definite channels, the joining and splitting of which may produce a not irregular pattern.

If it is true that the liquid of the intergranular space in glacial ice

is a salt solution, as suggested by Quincke,[3] the melting of the ice and the production of the furrows will take place at temperatures slightly below the freezing-point of water, owing to the lowered melting-point of the ice in contact with a salt solution. These furrows may thus be expected to develop in the interior of the glacier as well as in the outer portion which is subject to daily and seasonal temperature changes.

Elliptical wells.—On the sloping fronts of several of the Alaskan glaciers small elliptical cavities were observed, for which the name

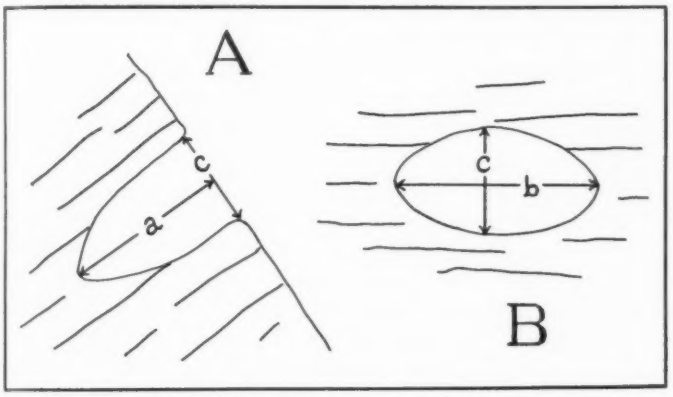

FIG. 2.—Elliptical wells: (*A*) vertical cross section normal to the ice front; (*B*) section parallel to the ice front and surface; (*a*) depth of well; (*b*) longer diameter, parallel to the ice-veining and roughly horizontal; (*c*) shorter diameter, normal to (*b*) and more or less vertical.

"elliptical wells" is suggested. No mention of these small depressions has been found in the literature; an attempt has therefore been made to describe them and to offer an explanation for their origin.

Such elliptical wells, seen in great numbers on Childs and Valdez glaciers, seemed to be mainly restricted to that part of the sloping ice front which carried much débris. Because of the orientation of these wells in relation to the veined structure of the ice, it is assumed that they are closely related to the ice structure. The wells (Fig. 2) are oriented with the longer diameter horizontal and parallel

[3] G. Quincke, "The Formation of Ice and the Grained Structure of Glaciers," *Nature*, Vol. LXXII (1905), pp. 543–45.

to the ice front, and also roughly normal to the direction of glacial motion. The shorter diameter, normal to the longer diameter, and roughly vertical, is proportional in length to the longer diameter. The longer diameter varies in length from 3 to 15 inches. The depth to which the wells penetrate the ice varies greatly; apparently it is a function of the amount of ablation and melting which has taken place on the surface of the ice at that point. The wells were oriented in a general way so that the longest diameter was parallel to the veining of the glacial ice.

The wells are apparently formed by the melting of a mass of porous ice, enclosed in the solid ice. Two explanations may be offered for the origin of the porous ice masses. First, they may represent snow-filled ablation cusps, formed at higher altitudes and brought to the surface by the melting of the superincumbent ice and snow. Observations did not reveal any one zone in which the wells were predominant, so that, if this is the correct explanation, they must represent many seasons of ablation cusps, with fillings of winter snow. Second, the masses of porous ice may represent air "bubbles" in the ice, formed by the concentration of air squeezed from between the snowflakes, as they were being transformed from snow, in the névé region, to glacial ice. Temperature changes, as well as pressure, would tend to force the concentration of air into the "bubbles" and also the expulsion of some of the air from the ice, through small fissures, allowing free passage to the surface. On warm days many small fissures on the glacier surface hiss and whistle as the air is forced from the ice beneath. Water sinking into the glacier would tend to force out the air and fill up the air "bubbles" which had formed.

FEATURES OF DRAINAGE

Undercutting of the ice by lateral streams.—Water from the melting surface of glaciers which does not find its way into the ice is likely to be concentrated into rather large streams, which may flow from the convex surface of the glacier into the moatlike depression that lies between the valley wall and the sloping ice surface (Fig. 3). These lateral streams undercut the ice of the glacier by melting, so that it is frequently difficult to descend from the surface of the glacier to the valley wall, for a thin ice cornice is developed by the undercutting.

Melting by these streams is greatly aided by the heat radiated from the bedrock of the valley wall adjacent to the glacial ice.

Undercutting was well developed at Mendenhall and Herbert glaciers, where it was found that the lateral streams did not flow for long distances under the ice cornice, but soon found their way under

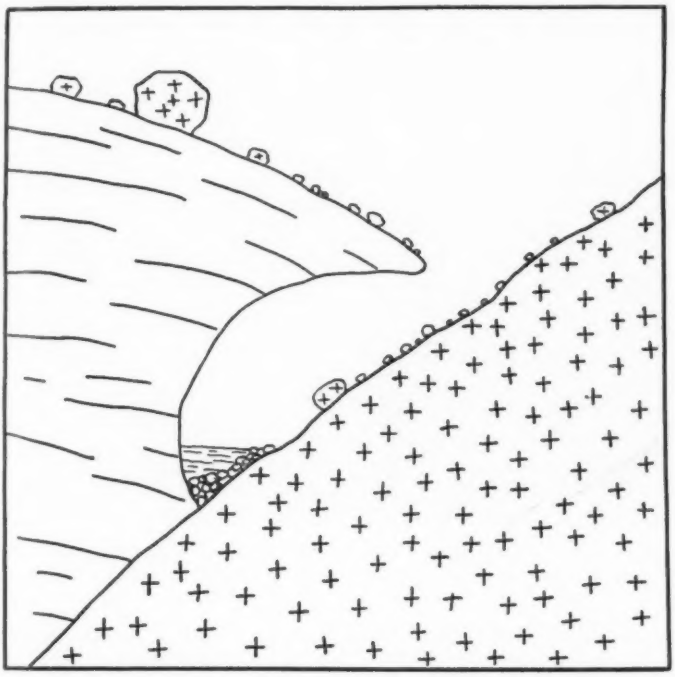

FIG. 3.—Cross section of junction of a glacier and valley wall, showing the undercutting of the glacial ice by the lateral stream. Superglacial débris has fallen from the surface and lodged on the valley wall or in the stream channel.

the glacier itself, through subglacial passages. Water in these streams flows only during the time of active melting of the glacier surfaces. During this period it is an important agent in the transportation of superglacial débris fallen from the sloping surface of the ice. The water carries such débris along the channels beneath the thin ice cornices and into the subglacial stream channels. During

periods of heavy rainfall such marginal streams may be increased by the runoff, both from the glacier itself and from the adjacent valley walls.

At Mendenhall Glacier (Fig. 4), the margin has been undercut and undermined until large fragments of ice have been broken from the moving central portion and have become stagnant, wasting, conical or ridgelike masses, covered with débris. This jumbled mass

FIG. 4.—Rugged lateral glacial margin along the south side of Mendenhall Glacier, caused by the undercutting of the ice by the lateral stream and the subsequent slumping of the unsupported ice. Note the several small elliptical wells on the ice surface in the foreground.

of ice blocks conceals the undercutting stream that produced the confusion.

All of the lateral streams observed were near the glacial termini and it must be borne in mind that the undercutting is common only where melting is rapid enough to furnish an ample supply of water. The streams diminish in size and activity as the snow line is approached, ceasing entirely in the region where the air temperature is constantly below the freezing-point of water.

Reversed drainage.—Because of the great variety of conditions to be found along the glacier termini and lateral margins, many pecul-

iar variations of the normal drainage are to be found. On the southern margin of Mendenhall Glacier, about 1 mile above the terminus, Nugget Creek, draining a small hidden glacier, descends from the mountains, plunges beneath the ice of Mendenhall Glacier, joining the subglacial drainage system, and finally debouches at the ice front as the headwaters of the Mendenhall River.

At the point where the creek disappears beneath the glacier, it has melted a large amphitheater-shaped depression into which the lateral streams flow. The stream along the glacier margin above this depression has had its gradient steepened at the point where it descends to join Nugget Creek as it plunges under the glacier. The former downstream continuation of the lateral stream below the melted depression is diverted in its upper reaches from its original course to the ice front into the nearby low point melted by Nugget Creek. In this manner some of the lateral streams have actually had their normal drainage reversed and now flow "up" the valley away from the glacial terminus.

Reversed drainage of this type has been observed by Bateman[4] on the Kennecott Glacier, and is of interest primarily in showing how complicated may be the drainage along the edge of an existing glacier. Observation of the irregularities and disruption produced by undercutting and slumping and melting along the lateral edges of the ice, as well as drainage changes along the constantly shifting ice front, leads to a more vivid conception of the complexity that must have existed in the drainage associated with the extensive Pleistocene glaciers.

Terraces.—Terraces on outwash plains were found to be especially well developed at Norris and Valdez glaciers (Fig. 5), and were also present, though not as well developed, at Spencer, Trail, Mendenhall, and Herbert glaciers. In all cases they have been formed by the shifting of the channels of streams draining the ice fronts, combined with a lowering of the stream gradient. A valley glacier debouches at the foot of the mountains; as it recedes slightly by the lowering of the ice surface, the outlets of the subglacial streams become lower and lower (provided the retreat does not carry the ice front to higher

[4] A. M. Bateman, "Notes on the Kennecott Glacier," *Geol. Soc. Amer. Bull. 33* (1922), p. 529.

altitudes), so that the terraces may be developed by agencies similar to those which cause the abandonment of the drainage valleys in the outwash material.[5] The terraces at Valdez Glacier show wide curves, corresponding to the sweeping meanders of the drainage stream. In all cases the terraces are associated with receding glaciers, for where the outwash plain is being built up by material from an advancing glacier there is probably little opportunity for terrace development.

FIG. 5.—Terraces on the gravel outwash plain in front of Valdez Glacier. Picture taken from a roche moutonnée near the glacial terminus. Valdez Arm in the background.

Russell has noted that terraces may also be found on the valley walls of a retreating glacier, being the result of deposition by marginal streams which are constantly lowering their levels.[6] No terraces of this origin were seen by the writer, but a more detailed study of the valley walls might have revealed them.

Abandoned valleys and lateral gorges.—The outwash plains in front of many of the retreating Alaskan glaciers are marked by abandoned stream channels, which in some cases are conspicuous features in the

[5] For a more detailed discussion of this method of lowering the outlets of the subglacial streams see the following section on "Abandoned Valleys and Gorges"; also Figure 7.

[6] I. C. Russell, "The Malaspina Glacier," *Jour. Geol.*, Vol. I (1893), p. 236.

topography of the outwash plain. A shifting of the drainage outlet, a lowering of the same, an increase in the amount of water from the melting ice, or a slight retreat of the ice front are some of the agencies which could bring about the abandonment of such valleys. The writer is of the opinion that a slight retreat of the ice front, caused by the lowering of the glacial surface, combined with the shifting of the main subglacial stream, could bring about the excavation of a new and lower channel for the main drainage stream. With a reduction of the glacier surface there would result a retreat of the ice front (Fig. 6). The material deposited by the glacier in front of the ice at its more advanced stage now assumes the rôle of a morainic barrier, through which the drainage stream cuts before the fosse between the ice and the barrier is filled with débris. When the streams have cut through the barrier, they are able to reach a new and lower gradient, the former channel having been abandoned.

The abandoned valley in the outwash material at the front of Herbert Glacier is thought to be of this origin (Fig. 7). The valley has been but recently abandoned, for the topographic map of the region, published in 1912,[7] shows the entire drainage passing through this valley, which is several feet higher than the floor of the present drainage system. Vegetation has not as yet had time to grow on the gravel of the abandoned valley. With the retreat of the ice front, resulting from a lowering of the glacial surface, and with a shifting of the drainage stream which forms the Herbert River a morainic barrier was developed, through which the stream cut a new valley on the opposite side of the ice front, so that the present drainage is on the south side of the glacier, the abandoned valley being on the north.

Several of the glaciers, when in a more advanced stage, so filled their valleys that water from the lateral streams, and sometimes from subglacial streams, was forced to flow along the valley wall and between partly uncovered roches moutonnées. These swift, débris-laden streams quickly cut deep, canyon-like valleys in bedrock (Fig. 8). Valleys of this type were seen at Bartlett, Spencer, Herbert, and Mendenhall glaciers. Spencer Glacier had two such gorges, one on each valley wall. At Mendenhall Glacier one of these valleys can be

[7] Adolph Knopf, "The Eagle River Region, Southeastern Alaska," *U.S. Geol. Surv. Bull. 502* (1912).

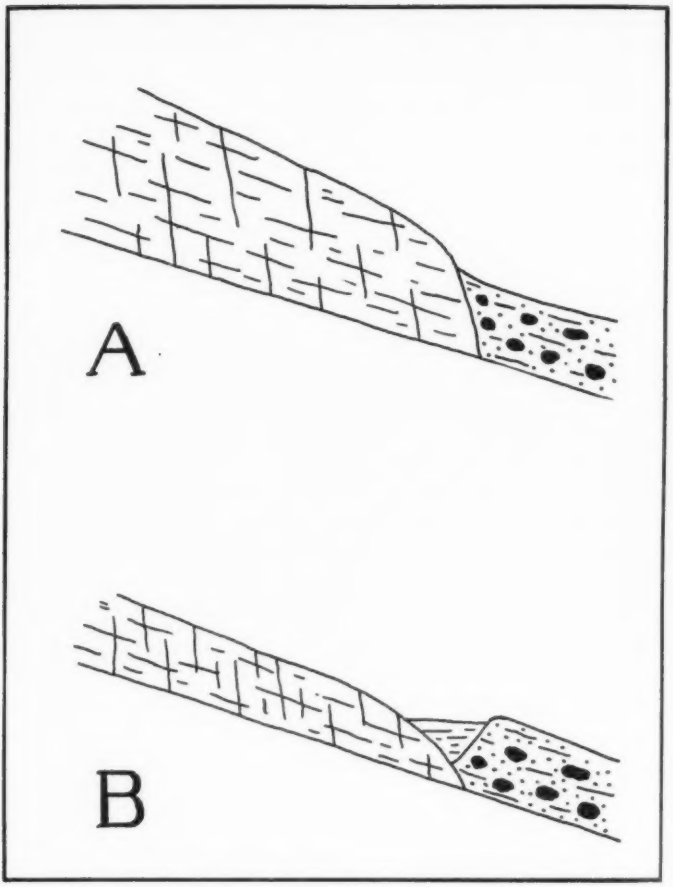

FIG. 6.—Reduction of drainage level by a lowering of the upper surface of a glacier through melting. (*A*) Glacier before there has been any marked reduction of the upper surface of the ice. Water drains from the ice front over the surface of the gravel outwash plain. (*B*) Upper surface of the glacier has been lowered by melting, with a consequent formation of an ice-front lake. There has been no retreat of ice terminus. Streams draining the frontal lake will cut through the material of the outwash plain to the level of the lake bed, thereby reducing the general level of the stream draining the ice terminus.

seen in the course of formation, for the large stream on the southern margin of the ice front is being forced to flow between two roches moutonnées, where it is cutting a narrow gorge. About 1,000 feet farther down the valley is another such gorge, now abandoned, which has been utilized as an automobile roadway to the ice front. At Mendenhall and also at Herbert glaciers waterfalls were found to be associated with such lateral gorges.

FIG. 7.—Abandoned valley on the north side of Herbert Glacier

No specific description of these features has been found in the literature, although there are doubtlessly many cases which could be cited. A careful search will probably reveal small lateral gorges formed along the retreating margin of the Pleistocene glaciers, where streams have been forced over bedrock in regions of moderate relief.

Crescentic streamline depressions.—On several outwash plains features were noted to which the name "crescentic streamline depressions" is here applied. A central depression with two channels pointing downstream, one on either side of the central, deepest part, outline the general shape of this feature. The tail-like channels were not of great depth and soon disappeared in the débris of the outwash

plain. The central deepest part varied in size from minute depressions to those 6 or 7 feet in width and 2 or 3 feet in depth. The length of the downstream channels is proportional to the width of the central

FIG. 8.—Postglacial gorge cut in bedrock on the north valley wall of Spencer Glacier, on the Kenai Peninsula.

depression measured normal to the direction of the flow of water over that particular portion of the outwash plain. These depressions were well developed on the outwash plains of Valdez (Fig. 9) and Spencer glaciers.

They are caused by the stranding of ice blocks on an outwash

plain where active deposition is taking place. Waters from the drainage streams are forced to flow around the stranded ice block, and thus, by concentration of flow, they increase in velocity and transporting power. The increased transporting power of the water is responsible for the development of the tail-like channels or "horns" of the crescent, which stretch in crescentic form downstream from the obstacle. The convex side of the crescent thus faces upstream.

FIG. 9.—Streamline depressions on the outwash plain of Valdez Glacier

As seen in Figure 9, the pebbles in the depressed channels are much smaller than those of surrounding areas. With the piling of débris about the melting ice block, enough velocity was developed in the waters forced around the ice to keep open and free from débris the lateral channels. Contemporaneous with the building-up of the outwash plain and the melting of the ice obstacle there was a decrease in the amount and velocity of water moving around the obstacle, so that the transporting power was lessened. Large cobbles were not moved across the outwash plain, and the smaller pebbles were lodged in the depressed lateral channels or horns.

Crescentic forms such as these are to be found in many natural

phenomena, every obstacle in any fluid stream tending to produce a similar pattern. Barchane dunes, crescentic holes melted in the ice covering of streams, and other common features are the results of this same principle. Recently a very comprehensive study of these patterns has been published by the Geological Institution of the University of Upsala, the name *Sichelwannen* being given to these crescentic shapes, developed by a variety of agents that operated, however, on the same physical principles.[8]

FEATURES OF EROSION

Ridged and furrowed gravel beds.—The feature to which the name "ridged and furrowed gravel beds" is here applied is one which has been illustrated by Grant and Higgins[9] in their report on the Columbia and Petrof glaciers, and illustrated and discussed by Gilbert[10] in the Harriman report. It consists of small ridges and furrows in the gravel of the outwash plains. The ridges are in general about 10–18 inches from crest to crest, the furrow in no case being more than about 3 inches in depth. The ridges are parallel to the movement of the glacial ice.

At Mendenhall Glacier (Fig. 10) they were well developed over an area of several hundred square yards. The plain is no longer being aggraded and the ridges and furrows are still sharp and well defined. Vegetation is now encroaching on them, and small alders, moss, and lichens are growing irregularly distributed among the closely packed gravel.

Two explanations can be offered for the origin of this feature. One is that the under surface of the advancing ice front may have been subjected to melting before the ice passed over the gravel outwash plain. A cuspate surface might thus have developed, the projecting cusps grooving the gravel as the ice passed over it. The grooving would later be exposed when the advancing ice front melted

[8] E. Ljunger, "Sapltentektonik und Morphologie der schwedischen Skagerrack-Kütse," *Bull. Geol. Inst. Uppsala*, Vol. XXI (1927–30), pp. 1–478.

[9] U. S. Grant and D. F. Higgins, "Coastal Glaciers of the Prince William Sound and Kenai Peninsula, Alaska," *U.S. Geol. Surv. Bull. 526* (1913), Plates VIII *A* and *B*, and XL*B*.

[10] Gilbert, *op. cit.*, pp. 77 and 78.

back. The regularity of the ridges over large areas suggests this mode of formation.

Another possible explanation is that they were caused by large cobbles embedded in the outwash material, as suggested by Gilbert.[11] A large boulder imbedded in the gravel might impress its form into the ice, and thus preserve in its lee a gravel ridge, as shown in Figure 11. This mode of formation might account for scattered ridges but would scarcely seem adequate to explain areas of regularly spaced ridges such as that shown in Figure 10.

FIG. 10.—Ridged and furrowed outwash plain in front of Mendenhall Glacier. The ridges are parallel to the direction of glacial movement.

Potholes.—Wherever swift glacial streams flow over the bedrock, potholes are likely to develop, for these streams are well supplied with rock fragments to be used as scouring tools. Potholes, developed by the swirling water of such streams, were seen on roches moutonnées at Valdez and Spencer glaciers, where they displayed all the characteristics of similar features in unglaciated regions. These potholes were always found in groups along abandoned stream channels and were associated with rounded surfaces, resulting from stream corrasion.

Water plunging into the moulins or rounded depressions on the

[11] *Ibid.*

surface of a glacier might develop potholes in the valley floor, if the moulins reached to that depth, in much the same way in which potholes are formed at the bases of waterfalls. Those developed in this manner would also be found in groups, concentrated at breaks in the slope of the valley floor, where moulins are developed in connection with crevassing of the ice. None was seen which could definitely be assigned to this origin.

FIG. 11.—Small cobbles which have impressed their form into the ice of Mendenhall Glacier as it advanced over them, leaving small ridges of débris on their leeward side.

FEATURES OF DEPOSITION

Dunes.—It was noted that at all glaciers the predominant summer winds blow down the valleys away from the glaciers. Conditions were such at Mendenhall Glacier that a large quantity of glacial sand, the grains averaging approximately 0.10 mm. in diameter, was piled by the winds into sand dunes on the outwash plain (Fig. 12). The dunes showed characteristic wind ripples and dune shape. They were not observed at the other glaciers visited, although several of considerable height rise on the delta of the Copper River only a few miles below the point where Childs, Miles, and other glaciers dump their débris into the river.

Dependent perched boulders.—The name "dependent perched boulder" is here applied to a pair of perched boulders, dependent,

one on another, for support. A case of this kind was noted at Herbert Glacier (Fig. 13). After this feature was photographed, the upper boulder was raised, releasing the lower, which rolled down the valley wall. Its support destroyed, the upper boulder also rolled down the slope when released. The stability was so perfect that the two had probably remained in this position for many years, since they were located more than a hundred feet above the present surface of the

FIG. 12.—Ripple-marked sand dune on the north side of the Mendenhall Glacier outwash plain, about 700 feet from the ice front of 1931. Note the hammer on the dune.

glacier. Evidently the boulders were left by the receding glacier at the time when the margin of the ice was at the level where they were now found. The lower one may have been left below an ice cornice; the upper one, rolling off the cornice, may then have fallen on the one below, thus establishing the equilibrium which remained after the ice had melted away. Again, several boulders might have fallen into the moat at the glacier margin, these two accidentally falling into a stable position, while the others rolled down the slope with the retreat of the ice. Many conditions may be imagined for the production of such a phenomenon, none of which could be offered as a sole explanation.

Numerous cases of double perching were seen, where one perched boulder rested upon another. One example of triple perching was also seen at Herbert Glacier. Cases of shelf-perching were not uncommon, where a boulder was lodged in a recess in the bedrock of the valley wall. This type of perching is the result of boulders rolling from the sloping surface of glaciers when the margin of the ice was level with the shelf or recess in the bedrock of the valley wall.

FIG. 13.—Dependent perched boulder on the south valley wall of Herbert Glacier

Rounding of cobbles.—Rock fragments which compose the material of the outwash plains seem to be dominantly rounded. Studies made at Mendenhall Glacier showed that the degree of rounding was high, almost perfect spheres being relatively common, as can be seen in Figure 14. Study of glacial cobbles showed that this condition was characteristic not only of Mendenhall Glacier but of all Alaskan glaciers visited. The débris carried on the surface of the glaciers is extremely angular, that carried englacially is well rounded, the latter type so predominating on the outwash plains that one might be led to the faulty conclusion that all glacial cobbles are rounded. The material of the outwash plains is primarily of englacial origin, the surface débris being so scattered among the rounded cobbles which

are spread over the frontal apron of a receding glacier that it appears negligible in amount.

At Mendenhall Glacier measurements were made along the southern margin of the ice, about ½ mile from the glacial terminus. The material consisted of striated, rounded, and snubbed[12] cobbles, together with a few scattered pieces of angular material of superglacial origin. The results of the measurements, tabulated below (Table I),

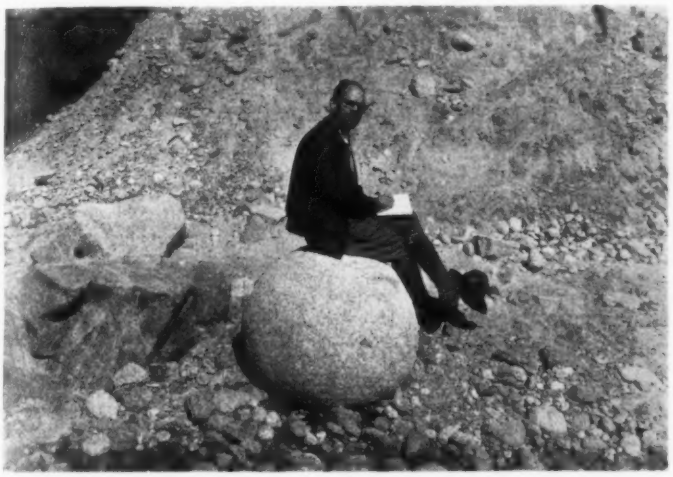

FIG. 14.—Unusually well-rounded glacial boulder from the main subglacial stream at Mendenhall Glacier.

show that the cobbles which range in size from a diameter of 64 mm. to 256 mm. are the most rounded.[13] On the outwash plain of Herbert Glacier measurements of cobbles picked at random showed a high degree of rounding, for with an average radius of 24.7 mm., the radius of curvature was 5.7 mm. and the index of curvature 0.23.

Breakage of rocks falling from the ice.—On warm days, débris is continually being dislodged from the sloping surfaces of the ice,

[12] "Snubbed is a pushing, or spalling-off of the lee, or hindermost end of a cobble because of the resisting side pressure as it moves along."—C. K. Wentworth, personal communication.

[13] C. K. Wentworth, "A Method of Measuring and Plotting the Shapes of Pebbles," *U.S. Geol. Surv. Bull. 730* (1922), pp. 91–114.

either along the margins of the glacier or along the steep-sided moraines on the glacier surface. The larger rocks are the first to move; and when they roll down the steep inclines, they are broken into smaller fragments as they dash against the rocks below. Breakage was made even more apparent when the rocks were precipitated over a marginal ice cornice, for then they struck either the solid rock of the valley wall or masses of rock débris. A very rude stratification, or

TABLE I

Diameter	Average Radius	Radius of Curvature	Index of Curvature
1 m. or more	661.0 mm.	10.0 mm.	0.02
256 mm. to 1 m.	202.2 mm.	25.5 mm.	0.11
64–256 mm.	60.15 mm.	12.0 mm.	0.20
8–64 mm.	23.4 mm.	3.7 mm.	0.16

separation of the larger from the smaller rock fragments, is developed in the débris thus moved by the melting of the ice. The position of the débris is continually shifted by this sliding until the fragments of rock are broken into pieces small enough to be carried away by the surface streams; or, if located along the lateral margin, they are brought to rest in the lateral moraine.

This action was especially noticeable on Grinnell and Childs glaciers, where boulders with diameters up to 3 feet were hurled down slopes of ice fully 150 feet in height, to be dashed into many pieces below. Russell noted an action similar to this on the Malaspina Glacier:

> Rocks rolling down the steep slopes are broken into finer fragments and are reduced in part to the condition of sand and clay. When the débris is sufficiently comminuted it is sometimes carried away by the surface streams and washed into crevasses and moulins. Not all of the turbidity of the subglacial streams can be charged to the grinding of the glacier over the rocks on which it rests, as a limited portion of it certainly comes from the crushing of the surface moraines during their frequent changes of position.[14]

Russell also mentioned the breakage of rocks which fall from ice pedestals.[15] Severe temperature changes tend to fracture the rocks on the glacier surface, so that any slight impact would cause them to split among the fractures.

[14] Russell, *op. cit.*, pp. 226-27. [15] *Ibid.*

FEATURES OF TRANSPORTED DÉBRIS

Angularity of superglacial rock fragments.—Fragments of rock carried on the surface of glaciers are angular, for they have not been subjected to the processes which would tend to round and abrade them. Glaciers obtain the surface débris by plucking the valley walls or by receiving talus material which has accumulated along the edge of the ice and been slowly transported by it. Where the glacier is relatively uncrevassed and the terminus is a low, rounded melting surface, there is little opportunity for rock fragments to become englacial and subject to the agencies which would tend to round and striate them. No rounded or striated glacial cobbles were found on the surfaces of the glaciers visited by the writer. Once the rocks become englacial and subject to the processes of rounding or faceting, they do not commonly appear again on the glacial surface, although Chamberlin reports well-rounded water-worn cobbles on the surface of Valdez Glacier, near the right-hand margin. He interpreted them "as having received their rounding by subglacial drainage, after which they were forced upward by differential movement within the ice along one of the inclined shearing planes and eventually appeared on the surface in a strip along the trace of the shearing plane."[16]

Mention has been made of the overwhelming preponderance of rounded material found on the glacial outwash plains, a preponderance explained by the fact that most of the débris transported by the ice is moved englacially. The sharp angular fragments are so scattered by the drainage streams and the rounded cobbles they are transporting that scarcely any angular rocks are to be found in front of the glaciers, even though their surface may be deeply veneered with sharp, morainal material. Chamberlin suggests that the rounding of the cobbles is far greater in the silt-laden streams issuing from the ice fronts of the glaciers, than in ordinary streams, so that a rounding might be obtained through a movement of less than one-quarter mile, which would be obtained only by many miles of transportation in ordinary streams.[17]

Agassiz found that, in the Pleistocene deposits, rounded cobbles

[16] R. T. Chamberlin, personal communication, October 13, 1934.

[17] R. T. Chamberlin, personal communication, October 13, 1934.

were far more predominant in America than in Europe.[18] He suggested that the broken character of the ground in Europe and the nearness of high mountain areas may have been responsible for the greater percentage of large and small angular rock fragments. There were probably no surface moraines of importance on the North American ice sheet, so extensive was the ice and so far removed from the high mountains.

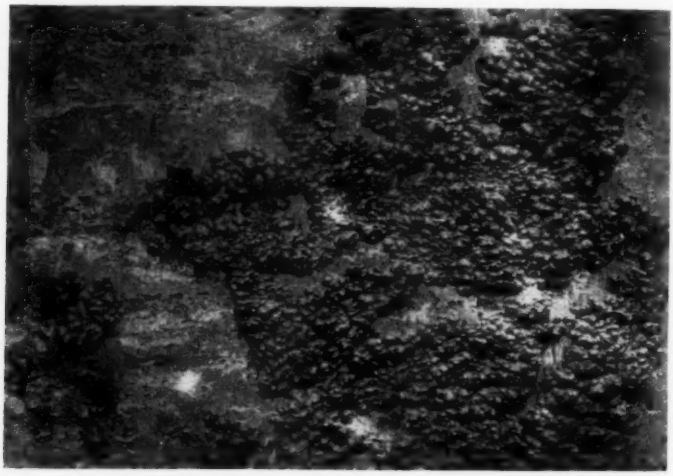

FIG. 15.—Mud balls, with a maximum diameter of 2 cm. on a vertical ice face at Mendenhall Glacier.

Mud balls.—Mud balls, first seen at Mendenhall Glacier, where they were well developed (Fig. 15), and subsequently noticed on all of the glaciers, have not been mentioned in the literature. They are small, rounded masses of mud, for which the name "mud ball" is here proposed, formed on the melting surfaces of the ice in favorable localities. Melting of the ice produces a rough papillose surface, owing to the more rapid melting of the intergranular areas. At the junction of these intergranular areas the melting is more rapid, for there more surface is exposed. It has already been noted that melting sur-

[18] Louis Agassiz, *Geological Sketches* (1903), p. 83.

faces of ice tend to assume a pointed form, leaving spherical cavities between the points. Into small cavities is washed the dust and fine rock-flour which accumulates on the surface of the glacier. By concentration, this powder assumes a ball-like form, becoming firm and compact by alternate wetting and drying. Continued melting of the ice on steep slopes or overhanging cornices allows the mud balls to roll or drop to the bottom of the slope, where large numbers of them

FIG. 16.—A mud-ball aggregate beneath an ice cornice, from which the pellets have dropped. Mendenhall Glacier.

accumulate to form noticeable aggregations (Fig. 16). Their diameters are locally as much as 15 mm.

Débris-covered ice cones.—This interesting phenomenon, familiar to those who have studied mountain glaciers or ice caps, has been given several names: "débris-covered ice cones," "sand cones," and "débris cones." The name "débris-covered ice cone" will be used in this study as more fitting than the other names, for the surface is not always covered with sand; nor is it a débris cone, but an ice cone covered with a thin veneer of débris (Fig. 17). The layer of débris usually has a thickness of about $\frac{3}{4}$ inch. Russell used the term "sand

cone,"[19] Reid used both "débris cone" and "sand cone"[20] and casually mentioned the fact that this feature was present on Muir Glacier.

Such cones were noted on all of the glaciers studied. They were mostly from 1 to 4 feet high, although larger ones, up to 10 and 12 feet in height, were found on some of the glaciers. The cones were pointed, the sides usually sloping more than 45°. When the débris on

FIG. 17.—Débris-covered ice cone on the surface of Herbert Glacier

the cones dried, it slipped off, exposing the ice beneath, and showed that the angle of slope of the cone's sides was greater than the angle of rest for the dry débris. The cones may owe their origin to several different causes which would tend to concentrate fine débris on the surface of the glacier. A thick layer of débris would protect the ice beneath from melting; as the surrounding surface was lowered by melting, the débris-covered portion would come to stand higher and higher, the edges melting before the center, to produce the conical shape.

[19] I. C. Russell, "Glaciers of Alaska," *U.S. Geol. Surv. Fifth Ann. Rept.* (1883–84), p. 350.

[20] H. F. Reid, "Studies of Muir Glacier, Alaska," *Natl. Geog. Mag.*, Vol. IV (1892), pp. 32–34.

Gilbert attributed the formation of these cones to the concentration of débris in crevasses.[21] Melting of the glacial surface would first reduce the clear ice of the intercrevasse area, the ice immediately below the débris in the crevasse being protected. In this manner there is brought about a reversal of relief of the glacial surface during the melting. It is a continuous cycle, for the débris covering of the ice cone is eventually reconcentrated in new crevasses. Frequently

FIG. 18.—A group of small débris-covered ice cones on the surface of Valdez Glacier. These are the remnants of a single large cone, which has disappeared through melting. A crevasse separates the cone on the left from the remainder of the group.

the cones occur in groups (Fig. 18), suggesting that they might be the scattered remnants of a former large cone. Débris sliding from a single large cone spreads out irregularly at the base, and scattered masses of débris accumulate which form new cones with an irregular group arrangement.

Much larger débris-covered ice cones have been described by Russell as follows:

> As the general surface of the glacier is lowered by melting, the partially filled holes gradually disappear and their floors, owing to the deep accumulation of débris on them, which protects the ice from melting, become elevated above the surrounding surface, in the same manner that glacial tables are formed.

[21] Gilbert, *op. cit.*, p. 202.

The débris covering these elevations slides down their sides as melting progresses, and finally a rugged pyramid of ice, covered with a thin coating of débris, occupies the place of the former lake. These pyramids frequently have a height of 60 or 80 feet, and are sometimes nearly conical in shape. They resemble "sand cones" but are of much greater size and are sheathed with coarser débris. The sand cones are usually, if not always, formed and melted away during a single season, while the débris pyramids require several seasons for their cycle to change.[22]

Large débris-covered masses of ice, several tens of feet high, may become separated from the main mass and, on melting, assume conical shapes, the melting being most rapid along the edges. Cones of this type may be found in front of receding glaciers, such as the Spencer and Mendenhall glaciers.

Glacial tables.—Glacial tables are probably the best known and described in the literature of all the minor features of glaciers, because of their striking appearance, wide distribution, and excellent development on small glaciers. It was interesting to note that on all of the Alaskan glaciers visited, relatively few well-developed glacial tables were seen. A general study of the cobbles which form the tables, made in June and early July, led to the belief that in Alaska the minimum size for a cobble which can develop a glacial table at this season of the year is an average diameter of 6–8 inches, and a thickness of approximately 3 inches. Glaciers visited in August and September had relatively few of these glacial tables, even boulders several feet in diameter resting directly on the ice surface, with no supporting pedestal. These conditions are the result of long hours of sunlight, the low angle of the sun in the sky, days of fog and mist, and the constant movement of the débris on the glacier surface during the summer months. Recent investigations on the size of rock fragments producing glacial tables have been made by Fryxell[23] on the glaciers of the Tetons of Wyoming. Differences in climate and latitude between Wyoming and Alaska are such that the development of glacial tables and the conditions affecting them are widely different, so that the minimum size cobble forming a glacial table in Alaska will be entirely different from that forming a table in Wyoming.

[22] I. C. Russell, "The Malaspina Glacier," *Jour. Geol.*, Vol. I (1893), pp. 231–32.

[23] Fritiof Fryxell, "The Formation of Glacier Tables, Grand Teton National Park, Wyoming," *Jour. Geol.*, Vol. XLI (1933), pp. 624–46.

STRUCTURE AND CREEP

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ABSTRACT

In regions of considerable topographic relief underlain by steeply dipping bedded formations, such as the Athens Plateau of southwestern Arkansas, the action of creep tends to move the edges of the up-ended beds down-slope, forming pseudo-folds which are in no way related to the underlying geologic structure.

The phenomenon commonly known as "creep" involves the transportation of unconsolidated surficial deposits through the action of gravity on materials affected by changes in temperature and in moisture content. Although the rate of movement of these materials is usually extremely slow, it varies with the steepness of the slopes on which the deposits rest and with the extremes of temperature and moisture content variation to which they are subjected, in rare cases reaching the proportions and suddenness of mud flows or rock slides.

Geologic literature contains adequate descriptions of creep and its associated phenomena[1] in so far as they are related to the soil coverings which are directly affected, but little mention has been made of the effects of creep on the underlying country rock itself. Howe[2] observes that in cases where the country rock is stratified and large rock masses are detached from their normal beds to creep down a slope, the masses tend to assume an attitude dipping into the slope. Twenhofel[3] comments that "the attitudes of large rock masses on a slope depend to a large extent on the original attitude of the rocks, but if the strata from which the blocks were derived were essentially horizontal, it will be found that large numbers have the original upper surface inclined into the slope."

These observations are already widely recognized. The practical oil geologist doing surface-structure mapping in the Mid-continent

[1] For a good summary with bibliography see W. H. Twenhofel and collaborators, *Treatise on Sedimentation* (Baltimore: Williams & Wilkins Co., 1932), pp. 92–103.

[2] E. Howe, "Landslides in the San Juan Mountains," *U.S. Geol. Surv. Prof. Paper 67* (1909).

[3] *Op. cit.*, p. 99.

region, being forced to look in the stream "breaks" for good exposures of the nearly flat-lying strata which underlie the region, soon learns to distrust dip observations even on strata which have every observable indication of being in place, and to insure his results by careful plane-table mapping. This is due to the fact that the stream "breaks" form steep slopes on which creep becomes especially effective.

These cases involve the action of creep on beds whose structural attitude approaches horizontality. But there are many regions underlain by steeply dipping stratified rocks where the influence of creep has even more structural significance than it has in areas of horizontally bedded rocks.

A notable example of such a region is the Athens Plateau, which forms the south flank of the Ouachita uplift in southwestern Arkansas. Here the underlying rocks are alternating beds of shale and sandstone of Carboniferous age which are standing on end in much of the area and very steeply dipping in the remainder. Their edges were truncated by a peneplain which was later uplifted and subjected to revivified erosion, etching the peneplain into submountainous topography with ridges standing in 300-foot relief over their associated valleys. (See De Queen and Caddo Gap, Arkansas Quadrangle Topographic Sheets.)

In this area most of the natural exposures of the underlying rocks are found on the steep ridge slopes, except in the rare places where superimposed streams, like the Little Missouri River between Daisy and Murfreesboro in Pike County, have cut through the ridges. But the most careful dip observations on these slopes lead to confusing and contradictory structural interpretations. This is due to the fact that the attitude of the beds has been strongly influenced by creep.

Recent highway development has exposed subsurface structure in new road cuts; and the discovery of cinnabar in Pike County has led to much deep trenching into the hillsides, so that the full effects of creep on the attitude of the underlying beds can be observed and evaluated. A study of thirty-seven road cuts and twenty-nine cinnabar exploration openings revealed the widespread influence of creep on surface dip. Nowhere was bedding at the surface observed to show the true dip.

The departure of surface dip from true dip ranges in magnitude from 1° to over 90°, depending on the local character of the beds affected and their position on the slope. Most susceptible to creep are shale members. Sandy shale members consisting of alternating sandstone and shale layers up to 1 foot in thickness show the most impressive effects of creep, because their response simulates folding. Even massive sandstone beds up to 14 feet thick are not immune.

The average depth to which the influence of creep extends in this area is about 6 feet, but in deep trenches indications of creep have been observed to a depth of about 40 feet in massive sandstone formations.

Down the bedding planes between the massive up-ended beds water seeps, freezes, and thaws, roots grow, and fragments of eroded sandstone work their way. The frost action acts as a lever, and the rock fragments act as wedges. The massive sandstone beds break across the bedding or move along fractures formed during the deformation which up-ended them. The ultimate effect is the formation of a fold formed, not by ordinary folding, but by progressive slight movement along originally closely spaced horizontal fractures. The movement is always down the slope, so that the axial plane of the pseudo-fold tends to parallel the slope and the beds dip into the hill regardless of their initial structural attitude.

In places a series of beds will act as a unit, bending down-slope as if it were a single bed. Such a unit is bounded by shale beds which have especial susceptibility to the wedge action of frost, roots, and hard rock fragments.

Figures 1 and 2 are photographs taken at the north and south ends, respectively, of a road cut in the northeast quarter of Section 11, T. 7 S., R. 25 W., Pike County, Arkansas. The photographs were taken about 500 feet apart. Surface dip in Figure 1 is about 50° S.; in Figure 2, 30°–80° N. The actual dip, as shown by the road cut exposing a depth of 20 feet or more, is about 80° S. It is important to note that the massive 10-foot bed of quartzitic sandstone shown at the left of Figure 2 is located very near the crest of the ridge. Its size, hardness, massiveness, and position on the hill would ordinarily give even a careful observer confidence that it could be used as an indication of true structural dip. The fact that it would mislead by 20° is

FIG. 1.—North end of road cut in the NE. ¼ of Sec. 11, T. 7 S., R. 25 W., Pike County, Arkansas. Looking east.

FIG. 2.—South end of the same road cut. Looking east

not as important as the fact that it would even indicate the wrong direction of dip.

Figure 3 illustrates diagrammatically the extreme sensitiveness of the formations in this area to the action of creep. It is a sketch of a road cut near the southeast corner of Section 22, T. 6 S., R. 25 W., Pike County, Arkansas. Here the long north slope of a very high ridge has been dissected by headward erosion of a minor stream gulley. The influence of creep on the major slope is profound, turning

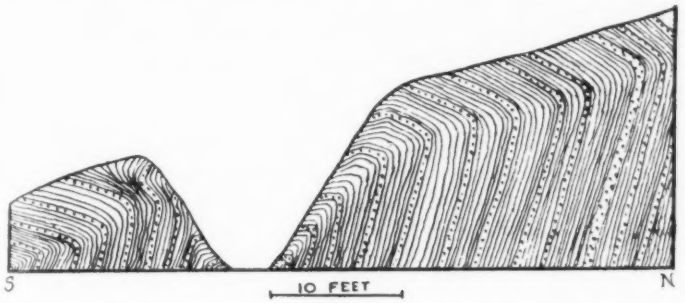

FIG. 3.—Sketch of road cut near SE. ¼, Sec. 22, T. 6 S., R. 25 W., Pike County, Arkansas. Note that the actual dip of the beds has been modified by creep along the long southward slope and the modified dip has been further influenced by creep along the slopes of the gulley.

the beds nearly at right angles, so that the surface dip to a depth of about 6 feet is approximately 30° N. whereas the true dip is approximately 70° S. The minor stream gulley runs along the strike of these beds, and creep along its slopes accentuates the turning on the north side and reverses the turning on the south side.

These observations lead to the conclusion that in this region particularly, and probably also in regions having similar geologic and topographic features, ordinary surface dip readings are wholly unreliable as indications of structure. The importance of this conclusion is emphasized by the fact that the interpretation of the structure of the Athens Plateau worked out before the deep artificial exposures were available[4] has had to be abandoned.

[4] H. D. Miser and A. H. Purdue, "Geology of the De Queen and Caddo Gap Quadrangles," *U.S. Geol. Surv. Bull. 808* (1929).

REVIEWS

Outlines of Physical Geology. By CHESTER R. LONGWELL, ADOLPH KNOPF, and RICHARD F. FLINT. New York: Wiley & Sons, 1934. Pp. v+356; figs. 297 and frontispiece. $3.00.

This is a condensation, with a little revision, of the *Textbook of Geology* by the same authors (1932). Technical terms are reduced in number; and, while minor phases of certain subjects are omitted, the condensation is quite uniform and balanced and has not been done at the expense of leaving out any whole divisions of the subject matter of physical geology. There are chapters on erosional processes, followed by chapters on sedimentary rocks, igneous rocks, volcanoes, diastrophism, earthquakes, and metamorphism. The concluding chapters take up mountains, land forms, and mineral resources. Minerals and topographic maps are treated in appendixes. The final discussion of mountains and land forms is an excellent teaching device for reviewing physical geology, and one which the teacher can well use to emphasize any or, indeed, almost all of the facts and principles studied earlier.

Examination shows that at least 102 of the illustrations are new; new photographs, many of them from the air, and new or redrawn diagrams, most of which will presumably be used in a future revision of the *Textbook*. Almost without exception the substitutions or additions are improvements. The printing of the photographs is noticeably improved, adding new and clearer detail (except in Fig. 41). The block diagrams are excellent. In many of the redrawn block diagrams, vertical exaggeration of scale has been reduced. In comparing the block diagrams of the Sierra Nevada in the *Textbook* and in the *Outlines*, it is seen that the less exaggerated one in the latter book (Fig. 243) is much the better. Volcanic and earthquake belts of the world are shown on a single map, rather than on separate maps, which will give the student a clearer picture of the relation of these belts to each other. The explanations or descriptions accompanying each figure are complete, clear, and useful.

The book is written for the beginning student; and his needs, preparation, and capacity seem to have been kept firmly in mind. The book is clear and accurate in definition and precise in description. It is especially suitable for those short courses in physical geology which most depart-

ments have to give to certain groups, and for which a larger textbook is too detailed. Yet it includes enough material so that the authors may find it displacing their *Textbook* in standard-length geology courses in some colleges where students without previous science training are permitted to take geology.

GEORGE W. WHITE

"Age of Gulf Border Salt Deposits," by LEVI S. BROWN, in *Bulletin of the American Association of Petroleum Geologists*, Vol. XVIII, No. 10 (October, 1934), pp. 1227–86; written critical discussion by D. C. BARTON, W. C. SPOONER, and reply by AUTHOR, pp. 1286–96.

Salt deposits, such as the mother salt series of the salt domes of the Texas-Louisiana Gulf Coastal Plain, are envisaged as formed in border basins in a cycle of transgression followed by regression of the sea. A normal seaward order of deposition will comprise: (*a*) a border series of clastic sediments of arid facies, and then on account of the freshening effect of water from the land, (*b*) limestone, (*c*) anhydrite-gypsum, and (*d*) rock salt. In the regression, the zones move seaward, and therefore the normal saline succession downward into the top of a salt deposit will be from the border facies through limestone and anhydrite into the rock salt.

A pre-Comanchean age of the salt is precluded by lack of known Permian, Triassic, or Jurassic strata and, therefore, of any border facies beds of those ages in the area. Limestones resting on the anhydrite cap at Smackover (Arkansas), Boggy Creek (interior Texas), and the limestone cap, with its inclusion of Navarro at South Liberty (Gulf Coast of Texas), are taken to indicate the normal saline sequence. Several characters show the salt to be of different age in the different basins (Arkansas, interior Texas-Louisiana, Gulf Coast). Analysis of the facies sequence in the Comanche sediments indicates the Smackover salt to be lowest Lower Comanche and the salt of the interior Texas-Louisiana basin to be Glen Rose. On faunal, paleogeographic, and climatic evidence, the age of the Gulf Coastal salt is from middle to late Upper Cretaceous.

This paper is regarded by specialists such as Spooner, Teas, Hanna, Weaver, and the reviewer as likely to confuse geologic thought on these salt domes and deposits, and possibly on salt deposits in general. The paper is well and interestingly written. The thesis of the paper in regard to these salt deposits reads plausibly, if one is not directly familiar with the fundamental facts. The argument of the paper is based on a concate-

nation of strained and improbable interpretations of basic data. The dissent of the reviewer and his colleagues, such as Spooner, Teas, Hanna, and Weaver, with whom he has had much discussion of this paper, is so drastic and extensive in regard to the author's interpretation of basic data of the domes and the area, his argument, and his conclusions, that within the space of this review it is feasible only to register that dissent. The reviewer would feel more charitable toward the paper if it were labeled as a speculation, for it is intriguing, although far-fetched, speculation; but the idea and the evidence submitted in the paper are labeled as definitely or highly conclusive.

DONALD C. BARTON

Lower Carboniferous Corals of China. By C. C. Yü. "Palaeontologica Sinica," Series B, Vol. XII, Fascicle 3. Peiping: The Geological Survey of China, 1933. Pp. 135; pls. 24.

Mr. Yü's volume, which approaches monographic comprehensiveness, is a scientific and technical discussion of the Carboniferous coral fauna of widespread areas in China. The author in the main avoids conclusions of philosophic or general import, and the work is obviously intended for specialists in the study of corals, whether their chief interest is morphology, taxonomy, or stratigraphic correlation.

The Introduction includes a chronological summary of the important work done since 1921 in correlating the Lower Carboniferous (Fenginian) beds of China, and an exposition of typical sections and faunal lists made available by recent studies by members of the Chinese Geological Survey. There is also a comparison of standard Fenginian sections from various provinces, with emphasis upon their correlation by means of coral zones.

The bulk of the paper is morphological description of 29 genera and 88 species of Carboniferous corals. The genera belong to the families Favositidae, Lophophyllidae, Hapsiphyllidae, Cyathophyllidae, Diphyphyllidae, Crepidophyllidae, Lithostrotionidae, Clisaxophyllidae, and Lonsdaleidae. The descriptions are lucid and complete; and their utility has been greatly enhanced by the author's familiarity with the literature, which has enabled him to compare the majority of the species with analogous European forms and to stress the differentiating characters. The new material brought to light by the analysis of so large a number of Asiatic species has also served to clear up hitherto obscure characters of a number of European corals. The work is amply illustrated by excellent photo-engraved plates.

Mr. Yü's paper is destined to occupy a key position in future attempts

to link the Carboniferous faunas and strata of the Occident with those of the Orient. One wonders that such an orderly work of high scientific quality can be produced amid the present chaos in China; one is even more impressed by the still masterly hand of the now invalided Amadeus Grabau, which continues to reveal itself in the pages of this and similar works of the Chinese Geological Survey.

BRANDON GROVE

The Limestones and Marls of Minnesota. By CLINTON R. STAUFFER and GEORGE A. THIEL. Minnesota Geological Survey Bulletin 23. Minneapolis, 1933. Pp. x+193; figs. 35; maps 58. $1.00.

The limestone, dolomite, and marl resources of economic importance in the state of Minnesota are given in this report. An introductory chapter on the commercial uses of limestone and marl precedes the two major divisions.

In Part I the limestones and dolomites of the state are treated. Following a chapter on the origin of limestone and dolomite, the occurrences are considered by counties. Numerous detailed sections and 160 chemical analyses are given.

In Part II the marl deposits are developed. Chapters on the nature and origin of marl, the relation of marl deposits to different types of drift, and methods of prospecting for marl are followed by the individual county discussions. Maps accompany the county reports wherever deposits of importance exist. It is regrettable that although a county outline map of the state is included, the names of the counties are omitted, thus making the text difficult for many readers to follow. A serviceable Index and a systematic arrangement throughout make the material quickly available.

GEORGE OTTO

Grundzüge der Geologie und Lagerstättenkunde Chiles. By PROF. DR. J. BRÜGGEN. Santiago, Chile: Mathematisch-Naturwissenschaftliche Klasse der Heidelberger Akademie der Wissenschaften, 1934. Pp. 362; maps and illustrations 70; photographs 6. M. 30, bound M. 33.

Dr. Brüggen, drawing material both from original researches and the published works on Chilean geology, offers for the first time a comprehensive account of the major features of the geology of that country. The first section of the report deals with the general geology, including rather detailed accounts of the pre-Tertiary geology, the structure, stratigraphy,

and physiography of the Andes, the coastal forms, vulcanism, and earthquakes. Several areas are discussed in considerable detail. The second section, comprising approximately one-third of the volume, contains a full account of the economic geology, treating in some detail the occurrence, origin, and resources of the metallics and non-metallics.

In view of the fact that this report brings together data heretofore available only in scattered reports, it represents an important contribution to the geology of Chile.

E. C. OLSON

Ocean Waves and Kindred Geophysical Phenomena. By VAUGHAN CORNISH, with Additional Notes by HAROLD JEFFREYS. Cambridge: University Press; New York: Macmillan Co., 1934. Pp. 159; illustrations 26. $3.75.

This book, treating ocean waves, sand waves, snow waves, waves in running water under gravitational control, and tidal bores, offers a wealth of observational data collected by the author in many widely separated sections of the earth. Interpretations of the natural phenomena are presented in cases in which the material is sufficient; problems for additional research are suggested where the data are insufficient. The illustrations consist of remarkable photographs of many of the cases discussed, which are not only valuable from the standpoint of science but are also highly artistic.

Notes by Harold Jeffreys supplement the author's observations with a theoretical consideration of several of the problems involved.

E. C. OLSON

Airways of America, Guidebook No. 1, The United Air Lines. By A. K. LOBECK. New York: Geographical Press, Columbia University, 1933. Pp. 207; figs. 124; maps 39; pls. 12. $2.50.

This book is the second in the series financed by the Kemp Memorial Fund. In the course of preparation the author made an airplane trip both ways across the continent, and among the fruits of this journey are most of the new and instructive photographs with which the book is illustrated. Thirty-nine route maps to a scale of about 1 inch to 19 miles with generalized geologic cross sections cover the strip of land along the airway between New York, Chicago, Cheyenne, and San Francisco. A trip by any means of transportation along the approximate route of the airway would be more interesting with this book as a constant reference.

More than half of the space is given to a running description of the route, to be read while riding. The chief emphasis is upon the physiography, and much of this is presented from the point of view of the surface expression of the underlying structure. Simple explanations of physiographic and structural forms are given in the footnotes. The supplement following the description of the route contains brief chapters on the physiographic provinces crossed, the agricultural areas and natural vegetation regions of the United States, climate and seasonal influences on flying, airways, and air navigation, and maps and note-taking, all to be read before starting the trip. The general and regional bibliography should be extremely helpful to one unfamiliar with geologic literature.

EDWARD L. TULLIS

Physics of the Earth: Part V, *Oceanography.* National Research Council Bull. 85. Washington: National Academy of Science, 1932. Pp. v+581.

The present volume of this series is written with the avowed purpose of being instructional to "the scientist not necessarily a specialist" in oceanography. This has been accomplished admirably.

To the geologist the chapter on the "Deep Sea Deposits" by L. W. Collet is most interesting. Among other facts of importance, he points out that deep-sea stratified deposits are likely to yield valuable information relative to changes in conditions during the Pleistocene glaciations.

E. H. Smith has contributed a chapter on "Ice in the Sea," parts of which are highly useful to the glaciologist. A. G. Huntsman discusses the relationship of oceanography to biology, and incidently paleontology and the origin of life. Charles Schuchert has contributed a paper on paleogeography, summarizing the progress made in this field of research.

H. W. STRALEY, III

Bulletin de la Commission Géologique de Finland 103. Helsinki-Helsingfors, 1933. Pp. 48; figs. 2.

Structural and pre-Cambrian geologists, petrologists, and minerologists will find portions of this bulletin of considerable interest. The first paper by Th. Sahlstein, "Ein Wort zur Microtektonik besonders im archaischen Grundgebirge," stresses the importance of a microtectonic analysis in the solution of complicated structural problems, and discusses the question of triclinic structural symmetry and "Plättung" structure, using the Lappland granulite as an illustration.

The four remaining papers are by P. Eskola. The first, "On the Differential Anatexis of Rocks," discusses the origin of granite magmas in general and enumerates, with numerous examples from American and European areas, a number of features which may be most satisfactorily accounted for by the theory of differential anatexis. A concise discussion of the characteristics and method of origin of arterites and venites may be of interest to many American geologists.

Eskola's second paper describes a very interesting association of chrome minerals in serpentine, quartzite, dolomite, and anthrophyllite-cordierite rock at Outokumpu in eastern Finland. Of particular interest is the occurrence of uvarowite-tremolite-tawmawite-pyrrhotite veins, which proves that chromium may be deposited hydrothermally. The unusual occurrence of chromite in dolomite is described, and two possible methods of origin are outlined. New determinations of optical, chemical, and physical properties of uvarowite, tawmawite, and chrome tremolite are presented.

The third paper is a short note crediting Stillwell with the first use of the term "metamorphic differentiation." The last paper, also a short note, may help to modify the popular conception that the Archean rocks have at some time been in the katazone. Eskola points out that the Archean rocks are seldom metamorphosed beyond the amphibolite phase, often only to the epidote phase, and therefore have not been subjected to greater metamorphism than would be found in the meso- or even the epizone.

GORDON RITTENHOUSE

Report of the Hawke's Bay Earthquake (3rd February, 1931). N.Z. Dept. of Sci. and Ind. Research, Bull. 43. Wellington, N.Z.: 1933. Pp. 116; figs. 28; pls. 21.

This report outlines the geologic, seismic, and catastrophic consequences and the possible cause of the Hawke's Bay earthquake of 1931 (R.-F. X). Various observed earthquake phenomena, including changes of sea level, ground level, and position of points, and the occurrence of tension cracks, pressure ridges, flow slips, and a mud blowout are described. A description of the geology of Hawke's Bay and adjacent portions of New Zealand summarizes current views of the New Zealand Geological Survey. Structural geologists will be interested in apparent close similarity of structures found in the Hawke's Bay region and structures obtained by Link in certain pressure-box experiments.

GORDON RITTENHOUSE

Geology of Central Alberta. By JOHN A. ALLEN and RALPH L. RUTHERFORD. Research Council of Alberta, Report No. 30, Edmonton. Alberta: University of Alberta, 1934. Pp. 40; Pls. 2; pocket map 1.

The text of this report, written to accompany a new geological map of central Alberta, is of a general nature. It describes briefly the physiography, structure, stratigraphy, and economic geology of the area. The colored geological map, drawn to the scale of 1 inch to 10 miles, utilizes much geological information not previously published. Several parts of the area which have not been studied in detail, and two small areas not studied at all have been mapped in a general way only.

E. C. OLSON

Geologic History at a Glance. By L. W. RICHARDS and G. L. RICHARDS, JR., Stanford University, California. Stanford University Press, 1934. Pls. 2. Educational edition, $0.80.

The two large, folded plates and brief explanatory notes, which compose this publication, give a synoptic account of the geologic history of North America. The first plate is made up of eight columns, the first seven of which depict the geologic ages, their duration, stratigraphy, lithology, distribution, and the events separating the geologic periods. The eighth consists of diagrammatic-photographic columnar sections of four areas of the United States, which, between them, contain all the large, representative divisions of the standard geologic column. The second plate presents a "rock-column building" constructed by fitting together diagrams and photographs to represent the geologic eras and periods, their proportionate duration, and their lithology.

This pictorial account of the geologic history of North America should be of interest to beginning students in geology, teachers of elementary classes, and to those interested in gaining a general knowledge of geologic history.

E. C. OLSON

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